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COMPENSATION AND AVALANCHE TECHNIQUES FOR TREE HARDENING

Volume I

Junction-Compensation Techniques for TREE Hardening

Goebel Davis, Jr., et al.

Bureau of Engineering Research
University of New Mexico
Albuquerque, New Mexico

Contract F29601-67-C-0017

TECHNICAL REPORT NO. AFWL-TR-67-95, Vol. I

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AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base
New Mexico

218

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FOREWORD

This report was prepared by the Bureau of Engineering Research, University of New Mexico, Albuquerque, New Mexico, under Contract F29601-67-C-0017. The research was performed under Program Element 6.16.46.01.H, Project 5710, Subtask 16.015 and was funded by the Defense Atomic Support Agency (DASA).

Inclusive dates of research were 20 August 1966 to 20 August 1967. The report was submitted 24 April 1969 by the Air Force Weapons Laboratory Project Officer, Dr. J. S. Nichols (WLDE).

This technical report has been reviewed and is approved.

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ABSTRACT

The reduction of the effects of transient gamma radiation on transistor circuits by using reverse-biased junctions placed at circuit points where they produce primary photocurrents that cancel out or compensate for the transient-radiation responses of the original circuit is evaluated. Approximate equivalent circuits which include junction compensation and approximate equations for engineering-design hardening criteria are developed.

Selected circuits exposed to transient ionizing radiation environments, with photocurrent compensation and without photocurrent compensation, were analyzed using a CDC 6600 digital computer and the CIRCUS analysis program. These computed results were compared to the responses actually observed when the items were exposed to a radiation environment at the Air Force Weapons Laboratory's 2 Mev flash X-ray facility.

With good design and for certain bias regions of operation, the peak magnitude of the transient-radiation response of an amplifier can usually be reduced by a factor of 3 to 1 to 10 to 1 for radiation levels up to approximately 0.5 x 10^{10} R/sec.

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CONTENTS

CONTENTS (cont'd)

ILLUSTRATIONS

ILLUSTRATIONS (con't)

ILLUSTRATIONS (cont'd)

ILLUSTRATIONS (cont'd)

ILLUSTRATIONS (cont'd)

ILLUSTRATIONS (cont'd)

ILLUSTRATIONS (cont'd)

TABLES

LIST OF PRINCIPAL SYMBOLS

A	junction area in cm^2
$\alpha=\|h_{fb}\|$	the h-parameter forward current transfer ratio for the common-base configuration
$\beta=g_m r_d$	forward current gain for common emitter configuration
C_b	a bypass capacitor
C,B,E	respectively the transistor external collector, base, and emitter terminal
C',B',E'	respectively the transistor-junction internal collector, base, and emitter points
C_c	a coupling capacitor
C_x	a compensation-junction voltage-source capacitor
D_1, D_2	ideal diodes
D_n	diffusion constant for minority electron in the p-type material
D_p	diffusion constant for minority holes in the n-type material
E_s	a signal source
E_x	electric field
erf	error function where $\operatorname{erf} x = \frac{2}{\sqrt{\pi}} \int_0^x e^{-x^2} dx$
g	electron-hole pair generation rate pairs/sec-cm^3
g_m	transistor forward conductance for the grounded emitter circuit
$\hat{I}_c$	the peak value of primary photocurrent from a compensation junction
I_e	the emitter current
I_n	electron current density

LIST OF PRINCIPAL SYMBOLS (continued)

I_p hole current density

I_{pp} the primary photocurrent generated in the collector-to-base junction of a transistor

$\hat{I}_{pp}$ the peak value of primary photocurrent

I_{sp} the secondary photocurrent

$\hat{I}_{sp}$ the peak value of secondary photocurrent

I_x the part of the primary photocurrent which flows through the emitter and is amplified

L_n diffusion length in the p-material, cm

L_p diffusion length in the n-material, cm

n electron concentration per cm^3

p hole concentration per cm^3

q the electron charge, 1.6×10^{-19} coulomb

R_b the equivalent external base resistor

R_c the external collector drop resistor

R_e the equivalent external emitter resistor

R_L the output load resistor

R_s the equivalent series resistance of the signal source E_s

R_x a compensation-junction isolation resistor

r_b transistor base bulk or spreading resistance

r_c transistor collector bulk resistance total

r_d the base-emitter junction equivalent internal diode resistance such that $\beta = g_m r_d$

r_e transistor emitter bulk resistance

r_i the h-parameter input resistance (h_{ib}) for the common-base configuration, with the base bulk resistance, r_b, subtracted out

LIST OF PRINCIPAL SYMBOLS (continued)

$\dot{\gamma}$	radiation-exposure dose rate in R/sec
T1, T2	transistors T1, T2, etc.
τ_n	lifetime in microseconds for minority carrier electrons in the p-material
τ_p	lifetime in microseconds for minority carrier holes in the n-material
$u(t), u(t-t_o)$	unit step function turned on at $t=0$ and $t=t_o$, respectively
μ_n	electron mobility
μ_p	hole mobility
V_b	base-emitter external bias source voltage
V_c	voltage from collector to ground
V_{cc}	the collector voltage source
V_d	the base-emitter junction internal contact potential
V_{eb}	base-emitter external bias source voltage
V_L	amplifier output voltage across R_L
V_o	voltage from emitter to ground
V_x	a compensation-junction source voltage
V_{xj}	the reverse bias voltage across a compensation junction
v	the voltage drop across r_d
W_t	depletion layer width in cm
x	assumed one dimension for current flow

A numeric subscript is added in some cases to indicate multiple use of the same symbol.

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SECTION I

INTRODUCTION

The effect of transient radiation on electronic components has become of vital concern to the military. It is mandatory that certain critical ground installations, aircraft, and missile systems be both reliable and effective and, if possible, not rendered temporarily or permanently inoperative due to exposure to a pulse of gamma radiation.

In a nuclear explosion, prompt gamma rays may either permanently or temporarily affect the operation of a missile. Since semiconductors are particularly sensitive to this transient radiation, the effects of the radiation must be considered in designing high-reliability defense electronic systems.

During exposure to transient pulses of gamma radiation, electron-hole pairs are created in semiconductor materials. In a back-biased semiconductor p-n junction, a pulse of current called the primary photocurrent flows across the junction. For a transistor, this pulse of current results in an excess of majority carriers in the base region. The excess charge is such that it tends to forward-bias the emitter, and hence, increase the flow of emitter and collector current. Thus, the transistor collector current may increase more than just the amount due to the transient-radiation-induced primary photocurrent. Such additional transient pulses of current are called secondary photocurrents.

It would be desirable to be able to design transistor circuits which have no response, or a greatly reduced response, during exposure to transient gamma radiation. This study presents numerous possible methods of reducing such effects in transistor circuits. The primary emphasis is on the addition of back-biased junctions at selected circuit points. During irradiation these extra back-biased junctions produce primary photocurrents which can be used to cancel out or to compensate for the transient-radiation responses of the original circuit.

Approximate equivalent circuit models which include methods of junction compensation are developed for various circuits. Utilizing these models, predictions are made for the resulting peak value circuit responses during irradiation. Approximate, engineering-design hardening criteria which determine the relationship among the circuit and device parameters are developed in the form of equations.

Some of the circuits were analyzed for transient-radiation response, utilizing the CDC6600 digital computer and the CIRCUS circuit analysis program. Selected hardened circuits were fabricated and experimentally tested under irradiation at the AFWL 2 Mev flash X-ray facility. These experimental results are compared to the calculated and computer-predicted responses.

SECTION II

BASIC RADIATION EFFECTS BACKGROUND INFORMATION

1. Basic Effects on Semiconductors

When a circuit containing semiconductor devices is exposed to a transient pulse of high-intensity gamma rays, device parameters change and induced spurious circuit responses appear. These effects are dependent upon the dose rate and pulse shape of the radiation. The predominant effect of the interaction of gamma rays with the semiconductor material is the production of free hole-electron pairs. In general, this results in transient-induced currents which last for the duration of the pulse or longer. In general, resistors, capacitors, inductors, electron tubes, etc., are relatively hard to a radiation environment (reference 1). It is the semiconductor devices which are highly radiation sensitive; therefore, careful circuit design and/or use of compensation techniques are required if these devices are to be used in critical applications. In addition to the transient effects, permanent or long-time annealing degradation to the device may occur at very high radiation levels. However, this study is restricted to the transient-radiation effects caused by radiation levels less than approximately 10^{13} R/sec.

During a pulse of transient gamma irradiation, semiconductor devices are perturbed (due to the radiation) from their original quiescent operating points for the duration of

the radiation pulse. When the radiation pulse has ceased, the circuit reverts to its initial operating conditions as soon as recombination of all excess hole-electron pairs is completed. Usually, for the radiation levels under consideration, no permanent effects are observed. In certain cases, the transient-radiation-produced currents may produce catastrophic failure of a device.

Transient gamma-ray sources are composed of a spectrum of energies. The dominant types of interaction of the gamma-ray photons with semiconductor materials are determined by the spread of the energies of the gamma-ray photons and the atomic number of the absorbing material.

The three possible types of interaction are (references 2, 3, and 4)

a. Photoelectric Effect. For materials with large atomic number and photon energies less than about 100 kev, the photoelectric effect is important.

b. Compton Effect. The Compton effect is associated with photon energies between 100 kev and 4 Mev.

c. Pair Production. The pair-production effect is observed for energies above about one Mev.

Hole-electron pairs are created directly by the gamma photons and by the secondary electrons or positrons (with reduced velocity). Energy of an amount several times the ionization energy is required for each hole-electron pair produced. The energy spread of secondary

electrons due to gamma radiation depends upon whether they were the result of the photoelectric effect, the Compton effect, or the pair-production effect. The first electron produced tends to have high energy. The electron spectrum is of the form of an inverse energy squared function. Succeeding generations continue to follow the same law and are capable of producing further ionizations as long as large-energy secondary electrons are present. The electrons will continue to lose energy due to inelastic scattering until they are trapped or recombined. This process continues until all of the excess electrons have been annihilated.

Both the holes and the electrons may or may not be current carriers. In certain cases, one or the other may be relatively immobile. For example, in ionized air around a semiconductor, it is primarily the electron which contributes to the current flow.

Both types of current carriers may carry current by the following two processes:

a. Diffusion current.

b. Drift current.

Equations which represent the hole and the electron current relationship for an assumed x-direction flow are given by

$$I_n = q\mu_n n E_x + qD_n \frac{\partial n}{\partial x} \tag{1}$$

$$I_p = q\mu_p p E_x - qD_p \frac{\partial p}{\partial x} \tag{2}$$

where

x = assumed one dimension for current flow

I_n = electron current density (ampere/cm^2)

I_p = hole current density (ampere/cm^2)

q = magnitude of electronic charge (1.6×10^{-19} coulomb)

μ_n = electron mobility (cm^2/volt-sec)

μ_p = hole mobility (cm^2/volt-sec)

n = electron concentration (cm^{-3})

p = hole concentration (cm^{-3})

E_x = electric field (volts/cm) in the x direction

D_n = electron diffusion constant (cm^2/sec)

D_p = hole diffusion constant (cm^2/sec)

In equations (1) and (2), the first terms are proportional to the electric field. These, by definition, are termed the drift current component. The two other terms are the diffusion current components which are proportional to the concentration gradient of n or p. The diffusion component of current tends to move a particle or carrier from an area of high concentration to an area of low concentration.

The electron-hole pairs produced by radiation are eventually eliminated by complex processes. These processes for semiconductors are described in reference 7 as follows:

In semiconductors, where the freed electron occupies a state in the conduction band, the electron returns to a valence band state in several sequential transitions by means of a recombination center. These recombination centers are discrete levels located near the center of the forbidden-energy gap, and are so-called because they aid the recombination between electrons and holes. This process simply amounts to the center first capturing an electron and subsequently capturing a hole. A recombination center thus has a large capture cross-section (probability that any localized level can capture an excess carrier) for both electrons and holes. In some cases, depending upon the atomic origin of the level, the level has a high-capture cross-section for one of the mobile carriers, but an extremely small cross-section for its mate. This level is called a trap, because it tends to trap the carrier for which it has the larger capture cross-section without capturing the other kind of carrier. Some trapping phenomena have been observed in which excess mobile carriers have been held for hours, or days, as in the formation of F centers in alkali halides.

In a typical germanium or silicon transistor the recombination time is usually of the order of a few nanoseconds to a few microseconds. The recombination occurs indirectly by use of a recombination center, and the rate of recombination is a function of the concentration of these recombination centers. The purer the material the longer is the lifetime of excess carriers. The maximum experimental value for very pure single crystal silicon is about 500 microseconds.

As is pointed out in the next subsection, the minority carrier recombination time has a major effect on the operation of solid-state devices in general, and on the resulting transient-radiation effects especially. Many of the present-day fast-speed switching diodes and transistors employ gold doping, which reduces the minority carrier lifetime to the order of a few nanoseconds.

2. Transient Effects on Junction Devices

a. Diodes. When a semiconductor p-n junction is irradiated with a pulse of gamma radiation, hole-electron pairs are created. These excess carriers cause pulses of current to occur. The semiconductor carrier recombination times, the radiation pulse shape and width, and many other factors influence the amplitude and the shape of these currents as a function of time. The recombination time of the minority carriers plays a dominant role in the basic response of the device to irradiation as well as in its normal electrical characteristics. The two basic categories of radiation response as influenced by recombination time are

1. A large recombination time. When the minority carrier recombination time is much greater than the radiation pulse width, the junction response increases in proportion to the radiation dose.

2. A small recombination time. For a recombination time that is short compared to the radiation pulse width, the p-n junction current is approximately proportional to the dose rate and hence, in general, has the same shape as the radiation pulse.

Figure 1 shows the characteristic change of majority and minority carriers in a one-dimensional germanium p-n junction (reference 7). The dotted lines show the carrier

concentration after irradiation, and the solid lines indicate the steady-state carrier concentration before irradiation. Figure 1a shows the typical carrier concentrations for the reversed p-n junction, and figure 1b shows the concentration for the forward-biased junction.

Electron-hole pairs are generated throughout the semiconductor material of a p-n junction during irradiation by a pulse of gamma rays. Due to externally applied fields and/or the junction contact potential across the depletion region, the hole-electron pairs generated in the depletion region drift across this region in a very short time. The current response experiences almost no delay with respect to the radiation pulse. This is called the prompt photocurrent component of current induced by irradiation.

Outside the junction transition region there is an increase in the minority carrier densities as shown by the dotted lines in figure 1a. The minority carrier density gradients increase near the junction and tend to cause an increase of diffusion current toward the junction. The transient-radiation-induced minority carriers which are within about one diffusion length of the junction reach the junction before recombining and form part of the radiation pulse current. However, most of the minority carriers further than about one diffusion length away recombine before reaching the junction and do not contribute to the current. This component of current which does reach the junction is

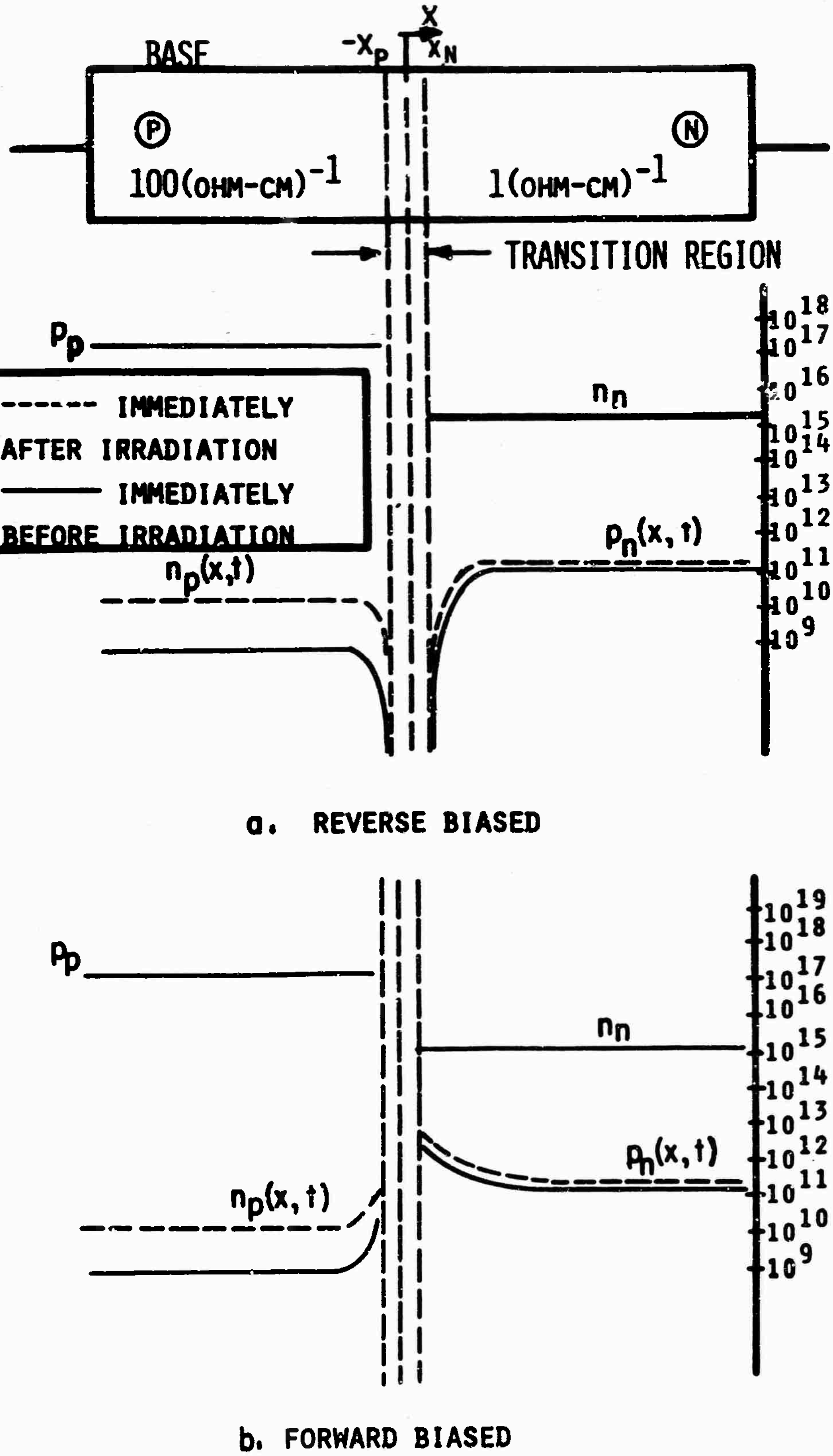


Figure 1. Approximate Minority and Majority Carrier Densities in a p-n Diode Before and Immediately after Irradiation

referred to as the diffusion or delayed photocurrent response. It is delayed in time because of the time required for it to diffuse to the junction. The total effect, including both the diffusion and the depletion components of radiation-induced currents, is a pulse of current in the direction of the leakage current in the reverse-biased diode.

For a forward-biased junction, the transient photocurrent is relatively small and is opposite in direction to the normal forward current flow. For most approximate analyses, the transient photocurrent response of a forward-biased junction can be ignored.

Assume that the ohmic contacts are located more than several diffusion lengths from the actual junction and that the junction is subjected to a rectangular pulse of ionizing gamma irradiation. Let $I_{pp}(t)$ be the resulting transient primary photocurrent response for a reverse-biased diode. A derivation of the expression for $I_{pp}(t)$ is given in several reports (references 5, 7, 8, 9). The result is

$$I_{pp}(t) = qAg[(W_t + \sqrt{D_n\tau_n}\ \mathrm{erf}\ \sqrt{t/\tau_n} + \sqrt{D_p\tau_p}\ \mathrm{erf}\ \sqrt{t/\tau_p})\ u(t)$$

$$- (W_t + \sqrt{D_n\tau_n}\ \mathrm{erf}\ \sqrt{(t-t_o)/\tau_n}$$

$$+ \sqrt{D_p\tau_p}\ \mathrm{erf}\ \sqrt{(t-t_o)/\tau_p})\ u(t-t_o)] \qquad (3)$$

where

$I_{pp}(t)$ = radiation-induced primary photocurrent, amperes

q = the electron charge, 1.6×10^{-19} coulomb

A = junction area, cm^2

g = electron-hole pair generation rate, pairs/sec-cm^3

W_t = depletion layer width, cm

D_n = diffusion constant for minority electrons in the p-type material, $cm^2/\mu sec$

τ_p = lifetime for the minority carrier holes in the n-material, μsec

τ_n = lifetime for the minority carrier electrons in the p-material, μsec

D_p = diffusion constant for minority holes in the n-type material, $cm^2/\mu sec$

$\left.\begin{matrix} u(t) \text{ and} \\ u(t-t_o) \end{matrix}\right\}$ = unit step function started at $t = 0$ and $t = t_o$, respectively

$$\text{erf } x = \frac{2}{\sqrt{\pi}} \int_o^x e^{-x^2} dx$$

The width of the depletion region is a function of the bias voltage (reference 5); thus, the depletion component of photocurrent increases with applied reverse voltage. Thus, I_{pp} is the sum of the depletion layer current (a function of voltage) and the diffusion current. For a depletion current large with respect to the diffusion current, I_{pp} is voltage sensitive.

Figure 2 is a plot of $I_{pp}(t)$ for a p-n junction diode for different relative values of L_p, L_n, and W_t. Figure 2a is a plot of an assumed rectangular pulse of radiation.

Figure 2b shows the theoretical $I_{pp}(t)$ associated with the rectangular radiation pulse when L_p, L_n, and W_t have about the same values. In figure 2c, the diffusion component is shown for $L_p + L_n >> W_t$. In figure 2d, the depletion component is shown for $W_t >> L_p + L_n$.

For many types of junctions (especially the base-to-collector junctions of an n-p-n transistor), the diffusion length in the n-material is much longer than that in the p-material. This is achieved by selective doping of the n- versus the p-regions. For this case, $L_n << L_p$ and the equation for I_{pp} reduces to

$$I_{pp}(t) = qAg[(W_t + L_p \operatorname{erf}\sqrt{t/\tau_p})\, u(t) - (W_t + L_p \operatorname{erf}\sqrt{(t-t_o)/\tau_p})\, u(t-t_o)] \qquad (4)$$

b. <u>Transistors</u>. The standard n-p-n transistor is comprised of two back-to-back p-n junctions, with the narrow p-region referred to as the base. The base-emitter junction is normally forward biased and the collector-base junction is usually cut off or reverse-biased. Most of the considerations discussed for the p-n junction apply for the transistor, with only slight modifications.

A transient pulse of gamma radiation applied to a transistor will generate electron-hole pairs throughout the semiconductor material. These excess carriers will drift across the junctions and diffuse toward the junctions.

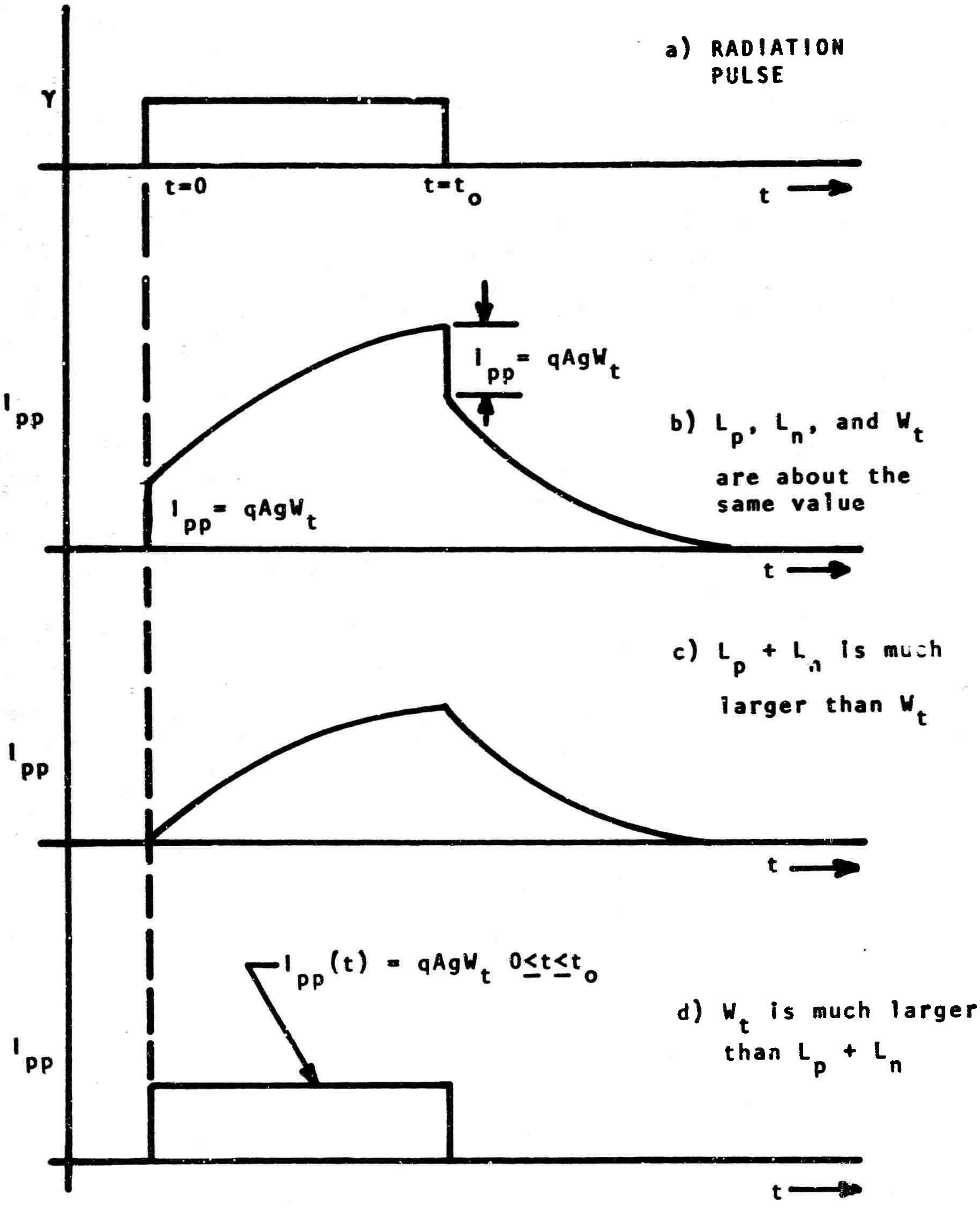


Figure 2. Transient Radiation Response of a Typical p-n Diode for Different Relative Values of L_p, L_n, and W_t

Just as for the p-n junction diode, a delayed component results from the diffusion currents and a prompt current results from the depletion layer components.

For discussion purposes, a biased transistor is shown in figure 3, with the base lead open. Note that the collector-base junction is reverse-biased. Electrons in the base become part of the delayed current by diffusing to the collector, leaving behind an excess positive charge in the base. Holes are also diffusing from the collector to the base area. Thus, an excess of positive charge is developed in the base region. The increase of positive charge in the base region tends to push the emitter-base junction closer toward forward biasing. This results in increased injection of electrons from the emitter to the base region which are available to diffuse to the collector-base junction. This excess charge is then available to drift across the junction. Thus, for a transistor, the transient-radiation-induced currents may increase by considerably more than just the primary photocurrent, I_{pp}. The transient current in excess of the primary photocurrent is called the secondary photocurrent or transistor beta multiplied current. The injected primary photocurrent carriers are essentially multiplied by the current-gain factor of the transistor. This point is clarified further in the next section.

Ignoring the secondary photocurrent, the primary photocurrent is due to two components:

1. A diffusion component.

2. A depletion component which increases with junction voltage.

For many transistors, the base width and depletion width are much less than the collector diffusion length, L_c. This is the result of the relative doping levels required in the different regions for optimum transistor operation. The essential effect is that fewer electrons diffuse from the base to the collector than holes diffuse from the collector to the base. For these types of transistors (such as the planar and mesa types), the primary photocurrent is developed predominantly in the collector-base junction. An engineering model for this situation is shown in figure 4. The primary photocurrent, I_{pp}, is treated as a current generator across the internal collector-base junction. In the use of this model, it is assumed that the external ac resistance in the collector-to-base circuit is not large. If the resistance is too large, a current-limiting effect on the primary photocurrent is produced; reduced transient current flow results. In the next section engineering models are developed which can be used in approximate circuit analysis.

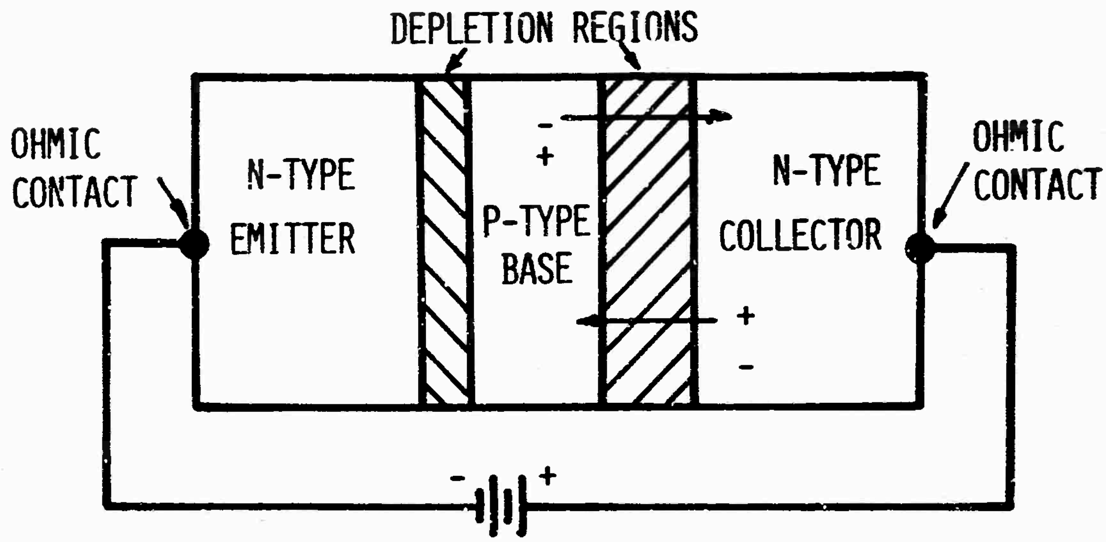


Figure 3. n-p-n Transistor During Irradiation

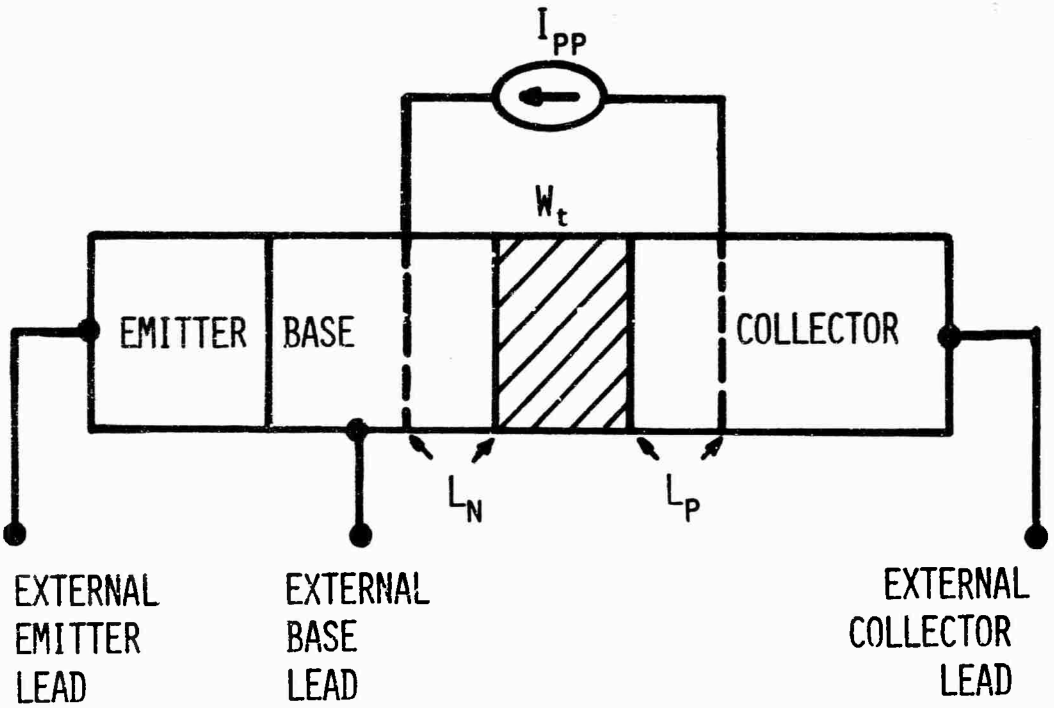


Figure 4. n-p-n Transistor Engineering Model, Including Radiation Photocurrent

SECTION III

APPROXIMATE THEORETICAL ANALYSIS AND DERIVATION OF ENGINEERING DESIGN CRITERIA FOR HARDENING CIRCUITS UNDER IRRADIATION

1. Preliminary Discussion

As discussed in the previous section, when a transistor is exposed to transient ionizing radiation, electron-hole pairs are created uniformly through the semiconductor material. A primary photocurrent, I_{pp}, will result (due mainly to the back-biased collector-to-base junction).

The flow of primary photocurrent across the junctions of the transistor results in a buildup of excess majority carriers in the base region of the transistor. This excess charge in the base is such as to forward-bias the emitter and to increase the flow of emitter and collector current. Thus, normally as an effect of the primary photocurrent (I_{pp}), the collector current (due to the ionizing radiation) may increase more than just the amount of Ipp. The additional current thus produced is called secondary photocurrent, I_{sp}, and it continues to flow until the excess base charge recombines or diffuses out through the base lead.

In practice, the transient pulses of collector and emitter currents are dependent on the biasing levels and the external circuit configuration. This dependence may be simply approximated or demonstrated on a quasi-steady-state

basis within an active linear region of transistor operation. Consider the generalized linear amplifier shown in figure 5. This basic amplifier normally would receive the base bias, V_b, from V_{cc} by use of a voltage divider. R_b is the equivalent external resistance as seen by the base.

An approximate ac equivalent circuit is shown in figure 6, which includes the transient-radiation effect (see the next subsection, where the terms are defined and the equivalent circuit developed). The peak of the collector leakage current due to the radiation is indicated by $\hat{I}_{pp}$. Assume that the portion of $\hat{I}_{pp}$ which enters the emitter is I_x. To determine I_x, the equations

$$\hat{I}_{pp} = \left(\frac{1}{r_d} + \frac{1}{r_b+R_b}\right)V_{B'} - \frac{1}{r_d} V_{E'}$$

and

$$g_m V = -\frac{1}{r_d} V_{B'} + \left(\frac{1}{r_d} + \frac{1}{r_e+R_e}\right) V_{E'} \tag{5}$$

must be solved for $V_{B'}$ and $V_{E'}$.

Then,

$$I_x = \frac{1}{r_d} V = \frac{1}{r_d} (V_{B'} - V_{E'}) \tag{6}$$

or

$$I_x = \frac{\hat{I}_{pp}}{1 + \left(1+\beta+\frac{r_d}{r_e+R_e}\right)\left(\frac{r_e+R_e}{r_b+R_b}\right)} \tag{7}$$

where $\beta = g_m r_d$ is the forward current gain at the final quasi-steady-state operating point.

This leakage current, I_x, is amplified by the transistor in such a way that the actual total change in emitter current (due to the radiation) is $(\beta+1)\, I_x$ and the total change in collector current is $\hat{I}_{pp} + \beta I_x$. The portion of $\hat{I}_{pp}$ that flows through the base is not amplified, i.e., $\hat{I}_{pp} - I_x$. Thus, the approximate peak value of the secondary photocurrent, $\hat{I}_{sp}$, is given by

$$\hat{I}_{sp} \doteq \beta I_x \tag{8}$$

Normally, r_e is small, so assume $r_e \doteq 0$. Then the simplified equation for I_x becomes

$$I_x = \frac{\hat{I}_{pp}}{1 + \dfrac{r_d}{r_b+R_b} + (1+\beta)\dfrac{R_e}{r_b+R_b}} \tag{9}$$

This is the relation to use for calculating I_x when neither R_e nor R_b is zero.

For the common emitter amplifier $R_e = 0$,

$$I_x\Big|_{R_e=0} \doteq \hat{I}_{pp} \frac{\dfrac{1}{r_d}}{\dfrac{1}{r_d} + \dfrac{1}{r_b+R_b}} \tag{10}$$

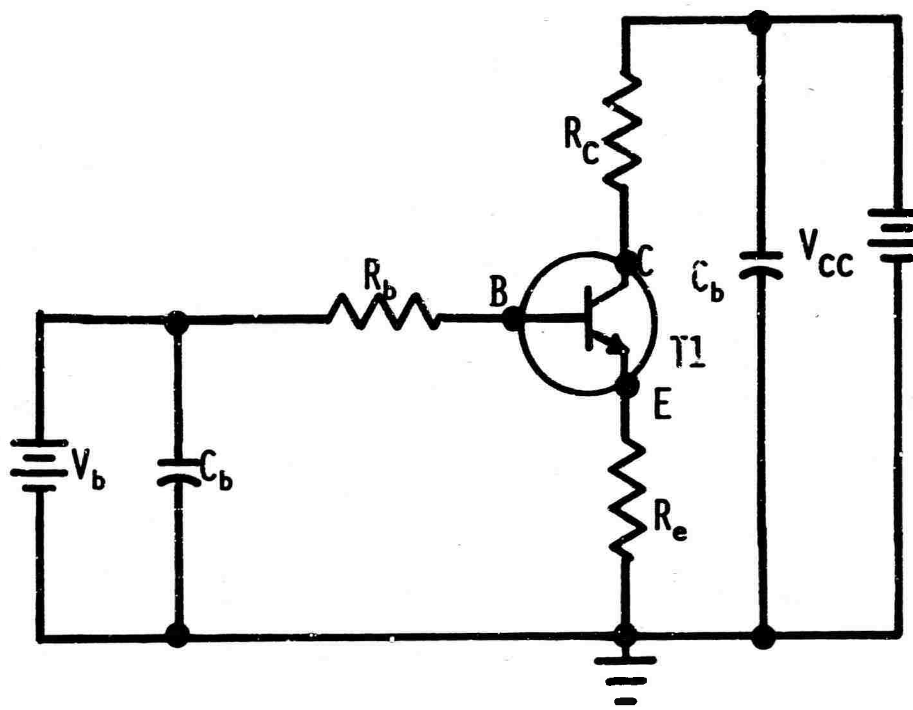


Figure 5. Generalized Linear Amplifier

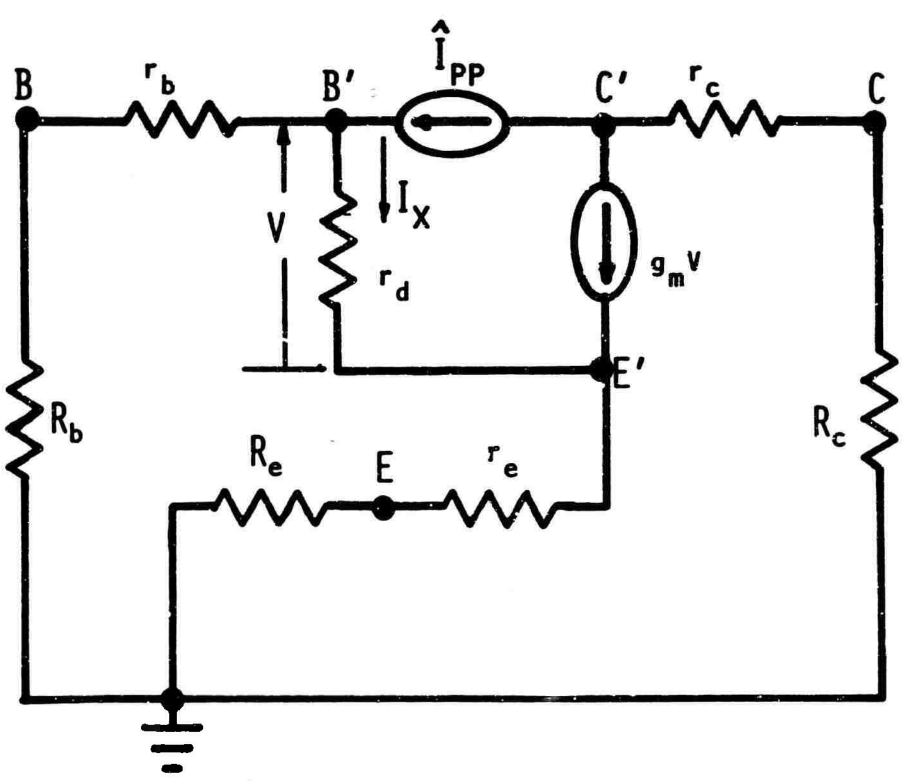


Figure 6. Generalized Linear Amplifier Equivalent Circuit

If $r_d << r_b + R_b$, equation (10) reduces to

$$I_x \Big|_{R_e = 0} \doteq \hat{I}_{pp}$$

Thus, for the common-emitter amplifier in the active region, most of I_{pp} flows to the emitter and a large secondary photocurrent flows through the collector.

For the common-base amplifier, $R_b = 0$,

$$I_x \Big|_{R_b=0} \doteq \frac{\hat{I}_{pp}}{1 + \frac{r_d}{r_b} + (1+\beta)\frac{R_e}{r_b}} \tag{11}$$

If $r_b << R_e$ and β is of normal value,

$$I_x \Big|_{R_b = 0} \doteq 0$$

Thus, for common-base amplifiers in the active region of operation, most of I_{pp} flows out of the base and very little secondary photocurrent multiplication occurs. The transient collector current flowing is approximately I_{pp}. The grounded base configuration is inherently less sensitive to transient-radiation effects than the grounded emitter circuit.

The flow of the radiation-induced primary and secondary photocurrents produces undesired transient responses at the outputs of transistor circuits. It is possible (in some cases) to nullify these effects by special circuit designs. In certain other cases, these effects can be nullified by the

addition of back-biased junctions at selected circuit points. These extra back-biased junctions produce primary photocurrents during irradiation which cancel out or compensate for the transient-radiation responses of the original circuit.

In this section, approximate large-signal equivalent circuits are developed for a number of transistor circuit compensation techniques. Approximate equations are derived to predict the resulting peak transient-radiation responses. These equations are used to establish the circuit criteria for transient-radiation hardening.

2. Equivalent Circuit for Common-Emitter or Common-Collector Amplifier

The basic equivalent circuit, which includes the transient-radiation effect, for the common-emitter amplifier (or common-collector amplifier) is developed in this section. In an exact transient analysis, the base-emitter diffusion and depletion capacitance, and the collector-base depletion capacitance would have to be included. If this model is used, the complexity of the circuits which are analyzed is increased. This, plus the fact that the exact shape of the ionizing radiation as a function of time is unknown, requires the omission of the circuit junction and stray capacitance or requires the use of computer-aided analysis. The resulting equivalent circuit is thus restricted to a steady-state or quasi-steady-state application. For the equivalent circuits to be valid, the applied radiation must have a

large pulse width or be changing at a rate less than the circuit time constants. It is for this reason that the radiation-induced primary photocurrent, I_{pp} (which is actually a function of time), is shown in the equivalent circuit as a peak value, $\hat{I}_{pp}$. For a square pulse of ionizing radiation, $\hat{I}_{pp}$ is the maximum value of the expression for I_{pp} as developed in section II, equation (4).

Thus, when these equivalent circuits are used to predict the transient-radiation responses, the results will actually be the peak values of the resulting responses. It should be kept in mind throughout this section that peak values are implied in all of the resulting equations, not response as a function of time.

Using information from references 10, 11, and 12 and previous experimental results as obtained by the author (reference 13), an approximate equivalent circuit which includes the radiation effect is shown in figure 7. As discussed in section II-2b, for most transistors the transient-radiation effect is simulated by placing a primary photocurrent generator across the internal transistor collector-base junction. The points marked C, B, and E represent, respectively, the external collector, the base, and the emitter terminals; and points B' and C' represent the internal junction points for the base and the collector. Thus, as only peak values are being considered, the radiation effect is taken care of by placing a peak primary photocurrent generator, $\hat{I}_{pp}$, from C' to B'.

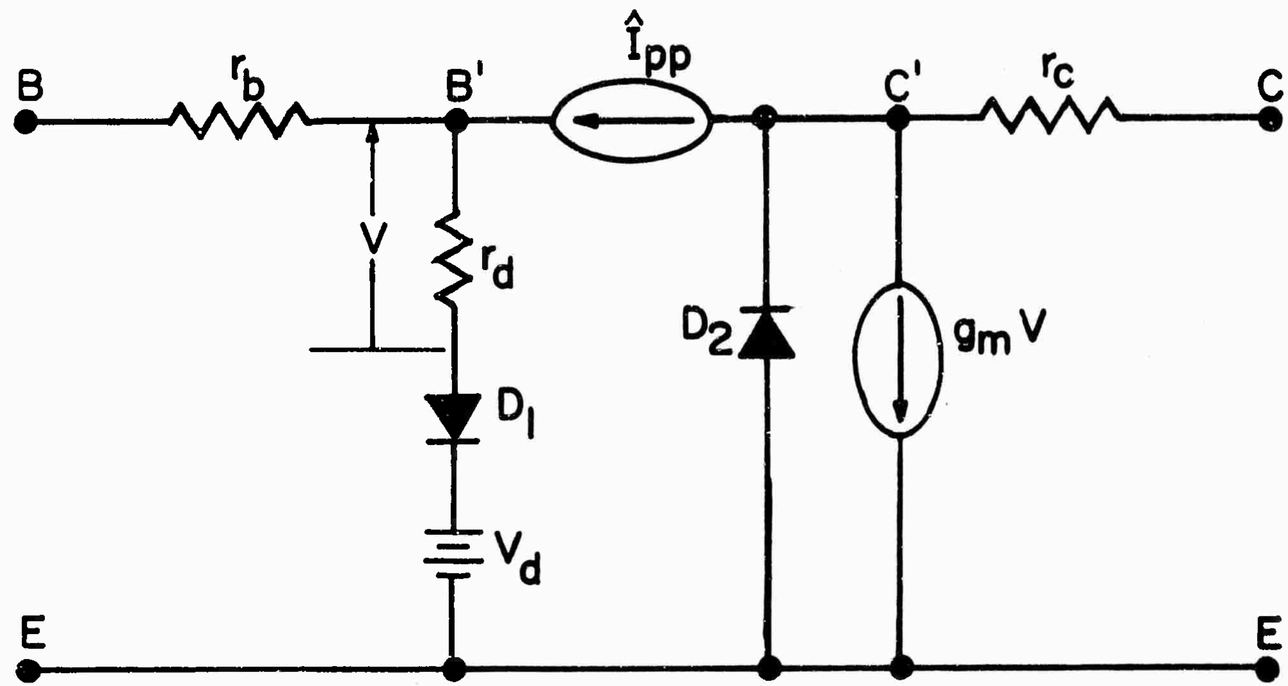


Figure 7. Equivalent Circuit for n-p-n Common-Emitter Amplifier

The model, as shown in figure 7, is an approximate large-signal, small-signal, or pulse-signal equivalent circuit. Operation in the cutoff, active, or saturation region is accounted for by the inclusion of the ideal diodes D_1 and D_2. Diode D_2 conducts whenever $V_{C'E}$ becomes negative for the saturation region of operation. The transistor is cut off for $V_{B'E}$ less than V_d, the base-emitter-junction internal contact potential. Thus, the diode D_1 and the contact potential V_d allow the model to account for the transition from cutoff to active region of operation.

Other circuit parameters to be defined are

r_b = the base bulk or spreading resistance

r_c = the collector bulk resistance

r_d = the base-emitter-junction equivalent internal diode resistance such that $\beta = g_m r_d$, where

β = the forward current gain at the final quasi-steady-state operating point

g_m = the transistor forward transconductance.

The numerical values of these parameters vary as a function of the quiescent operating point. This point would have to be determined in any numerical evaluations of the resulting equations. The basic form of the circuit in figure 7 is the hybrid-π equivalent (reference 14) for a transistor in the common-emitter configuration.

In figure 6, a bulk-emitter resistance, r_e, is shown in the equivalent circuit. The r_e is normally much smaller than the other device parameter resistances, and hence will be neglected. Also, the leakage resistances from collector to base and from collector to emitter are normally much larger than the other resistance parameters and may also be neglected.

Another limitation on the use of the circuit of figure 7 is that the output ac equivalent load be predominantly resistive and reasonably small (i.e., a low time constant). This will allow the output to follow the response of the transistor equivalent circuit. If the output equivalent load resistance is too large, a current-limiting effect on the primary photocurrent, I_{pp}, will result. This will not normally be a problem, as the ac equivalent load resistance is the parallel combination of the collector drop resistance, R_c, and the load resistance, R_L. As values for this parallel combination usually will run from about 50 to 500 ohms, significant current limiting of the primary photocurrent should not result.

Figure 8 shows the resulting total amplifier equivalent circuit, including the usual external circuit configuration. An input signal source, E_s, plus its equivalent series resistance is shown. For a pulse perturbation analysis about some quiescent operating point, both the coupling capacitors, C_c, and the bypass capacitors, C_b, can be considered as shorts.

Note that it is not required that the amplifier be used as a common-emitter amplifier. An emitter resistance, R_e, may be included without affecting the validity of the equivalent circuit. This would correspond to using degenerative feedback or a common-collector amplifier by making $R_c = 0$.

An n-p-n transistor is used in the circuits of figures 7 and 8. However, these circuits apply equally well for a p-n-p transistor if the polarity of all the current and voltage sources and the directions of the ideal diodes are changed.

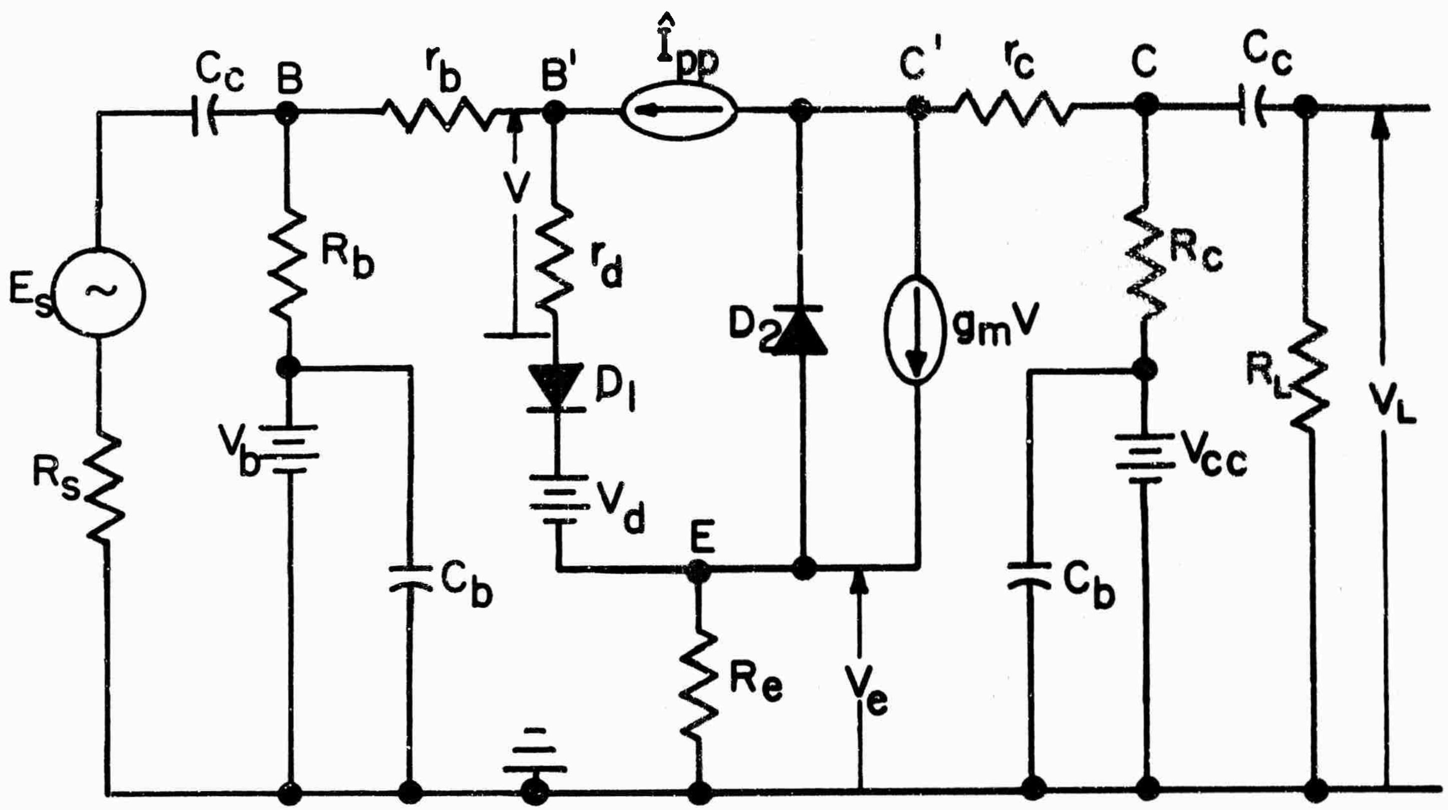


Figure 8. Common-Emitter Amplifier Plus External Circuitry

3. Equivalent Circuit for Common-Base Amplifier

An equivalent circuit model which includes the transient-radiation effect is now developed for the n-p-n common-base transistor amplifier. Most of the comments made in the previous subsection for the common-emitter model also apply to the model developed here.

As previously, the stray capacitance and the junction diffusion and depletion capacitances are omitted. Thus, the resulting equivalent circuit is restricted to a steady-state or quasi-steady-state type of situation. All results are stated in terms of the peak values of parameters which are time dependent.

Using references 10, 11, 12, and 13, the approximate equivalent circuit shown in figure 9 was developed. The transient-radiation effect is included by placing a peak primary photocurrent generator, $\hat{I}_{pp}$, across the internal transistor collector to base junction.

Operation in the cutoff, active, or saturation region is covered by the inclusion of the base-emitter junction internal contact potential, V_d, and the ideal diodes D_1 and D_2. The transistor is cut off for $V_{EB'} > -V_d$, and is saturated for $V_{C'B} < 0$. Thus, the equations defining the active region of operation are

$$V_{EB'} \leq - V_d \text{ and } V_{C'B} \geq 0 \tag{12}$$

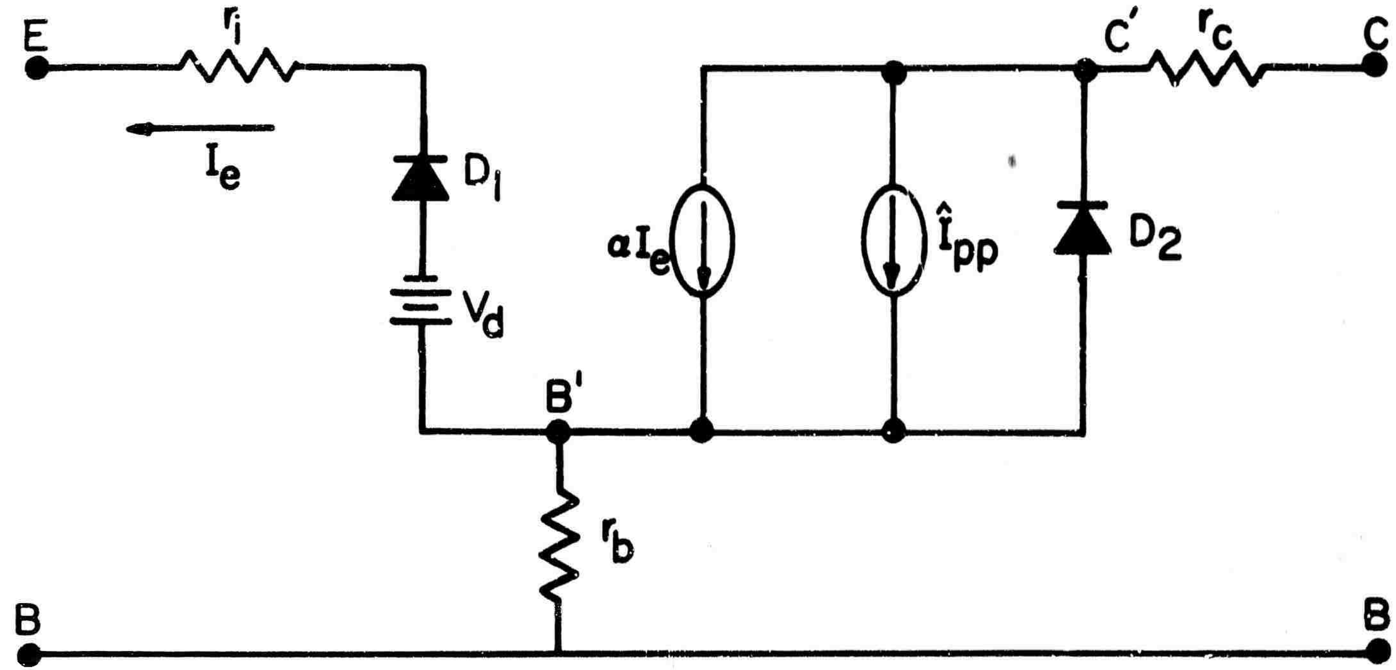


Figure 9. Common-Base Equivalent Circuit

Parameters not defined in the previous subsection are

α = $|h_{fb}|$, the h-parameter forward current transfer ratio for the common-base configuration

r_i = the h-parameter input resistance (h_{ib}) for the common-base configuration, with the base bulk resistance, r_b, subtracted out

I_e = the emitter current

In figure 10, the transistor equivalent circuit is incorporated into a complete common-base amplifier. The voltage, V_{eb}, is the external dc bias source. E_s is the signal source. For a pulse analysis, the coupling capacitors, C_c, and the bypass capacitors, C_b, are considered to be shorts.

Additional limitations for the equivalent circuit are

a. The small-value leakage conductance from collector to base, h_{ob}, is neglected.

b. The time constant of the output loading circuit must be small.

c. Most of the parameters are functions of bias conditions.

If p-n-p rather than n-p-n transistor operation is desired, change the direction of all ideal diodes and the polarity of all voltage and current sources.

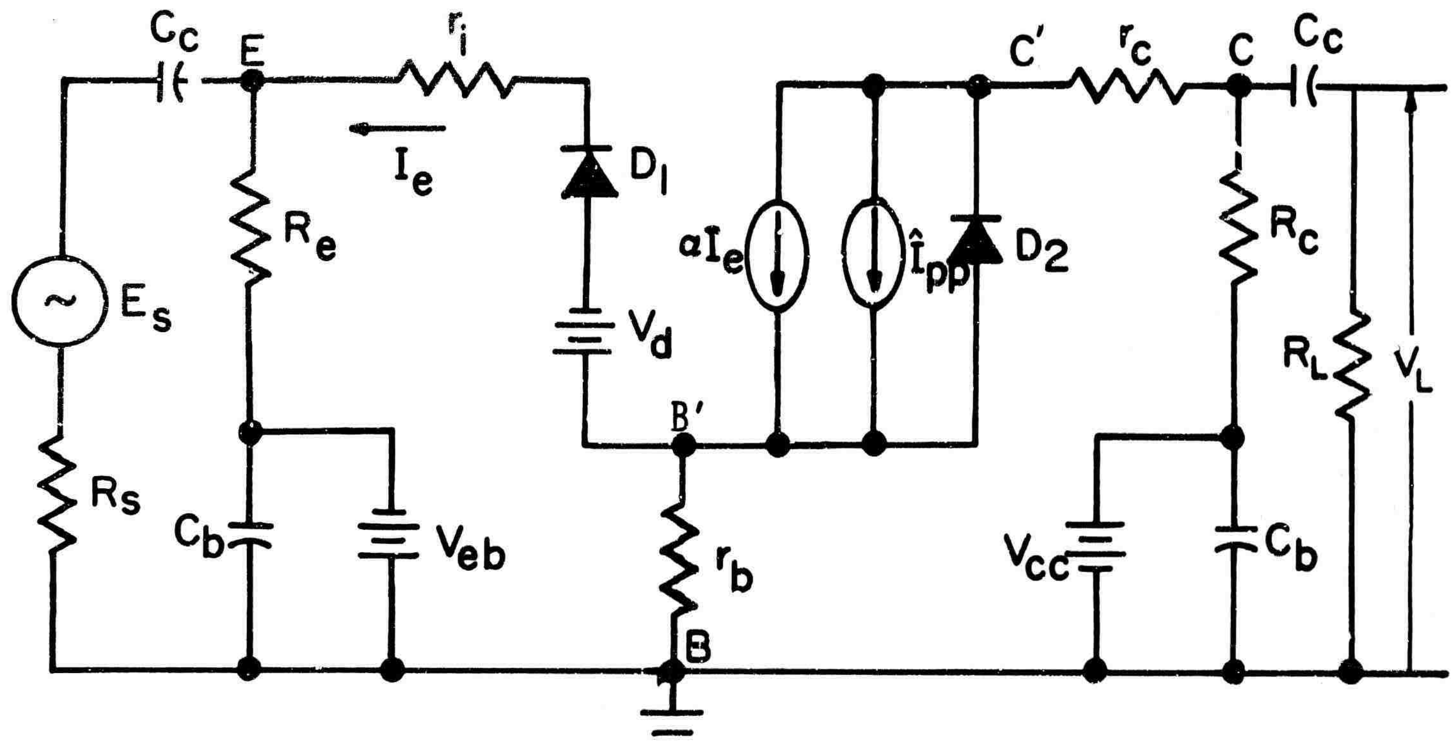


Figure 10. Complete Common-Base Amplifier Circuit

4. <u>Junction Compensation Techniques for Radiation Hardening of the Common-Emitter Amplifier</u>

a. <u>Collector-to-Base Compensation</u>. In section III-2, the approximate large-signal equivalent circuit was developed for the common-emitter amplifier. This model is now used to demonstrate the feasibility of several different methods of hardening this circuit to transient radiation, and to develop the circuit parameter relationships required to achieve this purpose.

The cutoff, active, and saturation regions of operation will be considered; however, all of the associated conditions relating to region transition criteria will not be derived. To develop these relations, the sum of the dc and the peak values of the transient-radiation-induced voltages should be derived and applied to the mathematical relations associated with transition from cutoff to active region or from active to saturation region. Thus, it is assumed that during irradiation the transistor stays approximately in its original quiescent region of operation because of the proper performance of the compensation.

Consider the circuit of figure 11. This circuit is a basic common-emitter amplifier with a compensation junction added for radiation hardening. For simplicity, the input signal generator, E_s, and the source resistance, R_s, have been omitted. Just consider R_b actually to be $R_b \| R_s$.

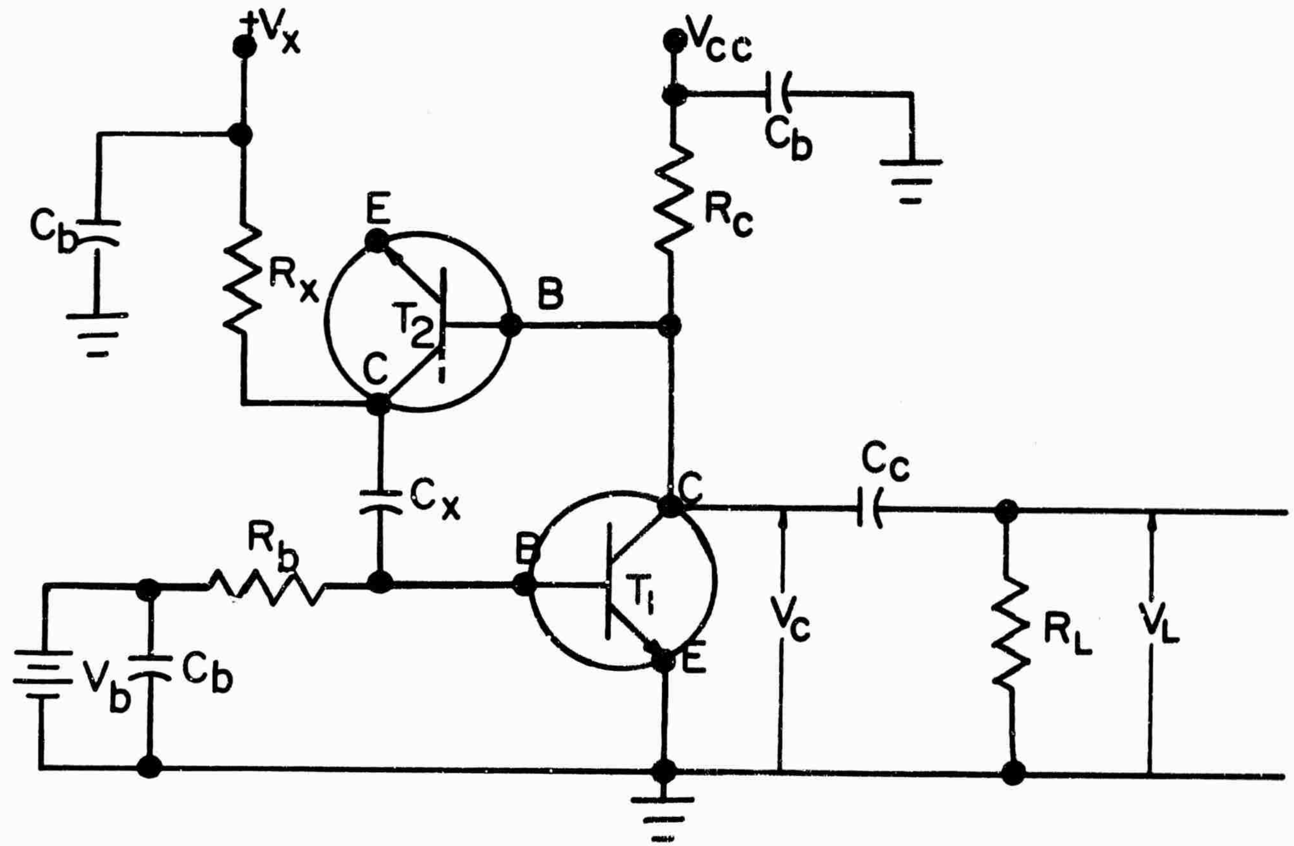


Figure 11. Circuit for Common-Emitter Amplifier with Collector-to-Base Cancellation

A properly biased junction (the collector-to-base junction of transistor T2) is connected from the collector to the base of T1 to directly cancel the transient radiation effects. V_x, the compensation junction source voltage, must be large enough to assure that the junction is always reverse-biased. The compensation junction voltage, V_{xj}, can be adjusted by varying the source voltage V_x. The voltage, V_{xj}, must be limited to a value below the collector-base breakdown voltage. The equation for the voltage V_{xj} is

$$V_{xj} = V_x - V_c \tag{13}$$

where V_c is the quiescent value of collector voltage for T1. The collector-base voltage for T1 is

$$V_{CB} = V_c - V_{BE} \tag{14}$$

If there is a significant depletion component of photocurrent, it is possible to adjust or "tune" the magnitude of the primary photocurrent from the compensation junction by changing V_{xj}. Thus, if the compensation technique requires that $\hat{I}_c = \hat{I}_{pp}$, one should make $V_{xj} = V_{CB}$ if the two transistors are identical in every respect. Note that the emitter of T2 is not connected. Thus, a diode can be used for the compensation if one with suitable radiation

characteristics is available. R_x should be large enough to give good isolation and to assure that the input of the amplifier is not loaded excessively. C_x should be large enough so that no significant change in voltage across it occurs during the time that the radiation-induced primary photocurrent flows. A series of computer program runs was made for the common-emitter amplifier with the values of C_x and R_x varied during simulated irradiation. The results showed that C_x should be at least 0.1 μf and R_x should be at least 0.1 meg. Experimentally, values of R_x = 2 meg and C_x = 1 μf were successfully used during radiation tests of several amplifiers using this method of compensation.

Figure 12 shows the complete transistor equivalent circuit, plus the external circuit. For this circuit to remain in the cut off state, $V_{B'E}$ must stay less than V_d during the radiation pulse. That is,

$$V_{B'E} = V_b + \hat{I}_{pp} r_b + (\hat{I}_{pp} - \hat{I}_c) R_b < V_d \qquad (15)$$

Note that without the compensation ($\hat{I}_c = 0$), I_{pp} tends to drive the transistor into the active region with a resulting large photocurrent development. With the compensation, $\hat{I}_c$ tends to cancel out the increase of $V_{B'E}$ across R_b. If it is required that the transistor stay in the cut off mode, it follows from equation (15) that

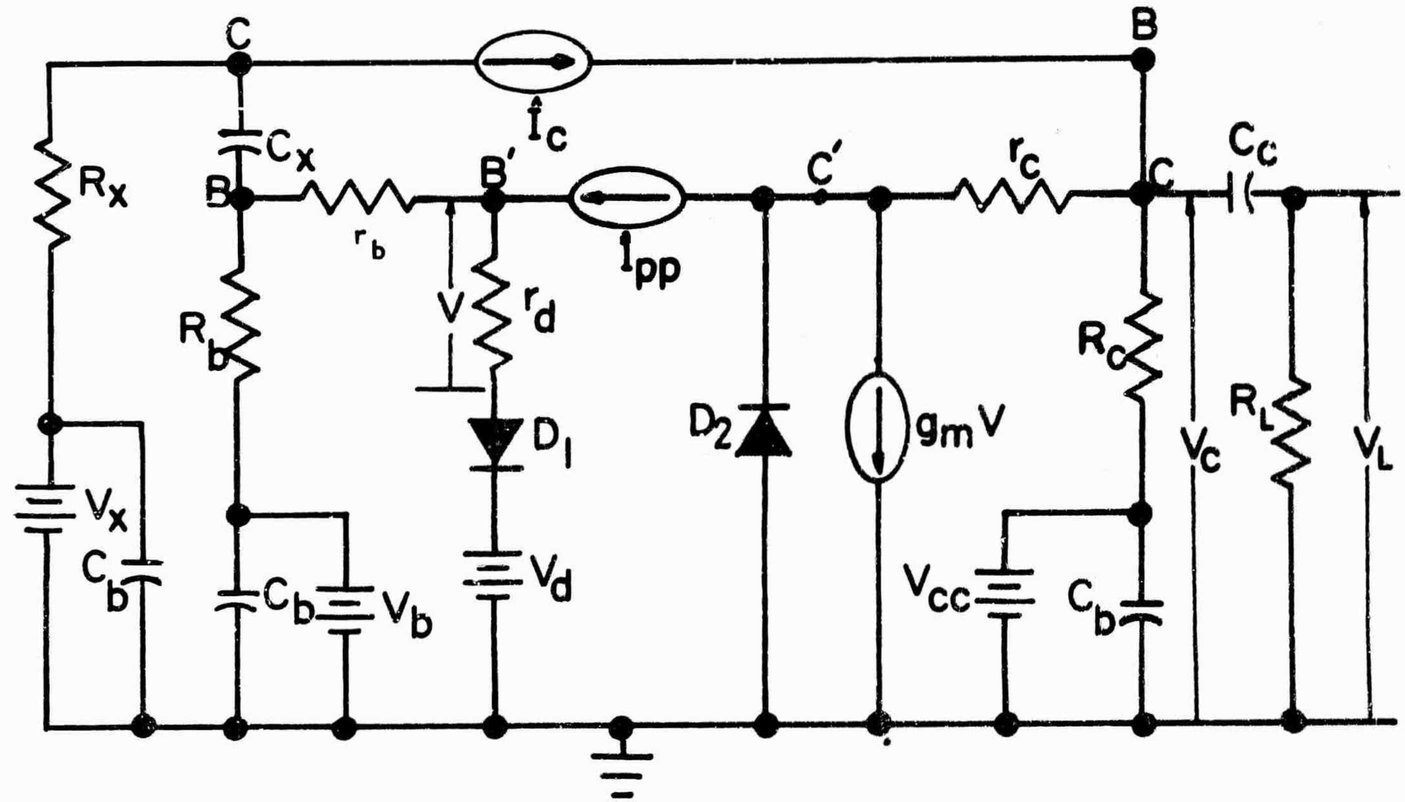


Figure 12. Equivalent Circuit for Common-Emitter Amplifier with Collector-to-Base Cancellation

$$\hat{I}_c > \frac{1}{R_b}\left[V_b - V_d + \hat{I}_{pp}(r_b + R_b)\right] \qquad (16)$$

Normally, $r_b << R_b$. Then, if $I_{pp} \doteq I_c$, the device stays in cutoff for $V_b = 0$, provided $\hat{I}_{pp}\, r_b < V_d$. This is usually true for low radiation levels.

Cutoff Region. Figure 13 shows an ac equivalent circuit with the unit remaining cut off. The resulting expression for the peak pulse output voltage during irradiation is

$$V_L \doteq (\hat{I}_c - \hat{I}_{pp})\, R_c \| R_L \qquad (17)$$

To achieve proper compensation, make

$$\hat{I}_c = \hat{I}_{pp} \qquad (18)$$

Even if exact cancellation is not achieved, the output is relatively low, as no secondary photocurrent is developed.

Active Region. Figure 14 shows an ac equivalent circuit for the active region of operation. It is assumed that the unit is not driven into saturation. The resulting expression for the peak pulse output voltage is

$$V_L = \left[\hat{I}_c - \hat{I}_{pp} - \beta\, \frac{(R_b + r_b)\hat{I}_{pp} - R_b \hat{I}_c}{R_b + r_b + r_d}\right] R_c \| R_L \qquad (19)$$

where $\beta = g_m r_d$.

Usually one can assume

$$R_b >> r_b + r_d$$

Then,

$$V_L \doteq \left[(1+\beta)\hat{I}_c - (1+\beta+\beta\,\frac{r_b}{R_b})\, \hat{I}_{pp}\right] R_c \| R_L \qquad (20)$$

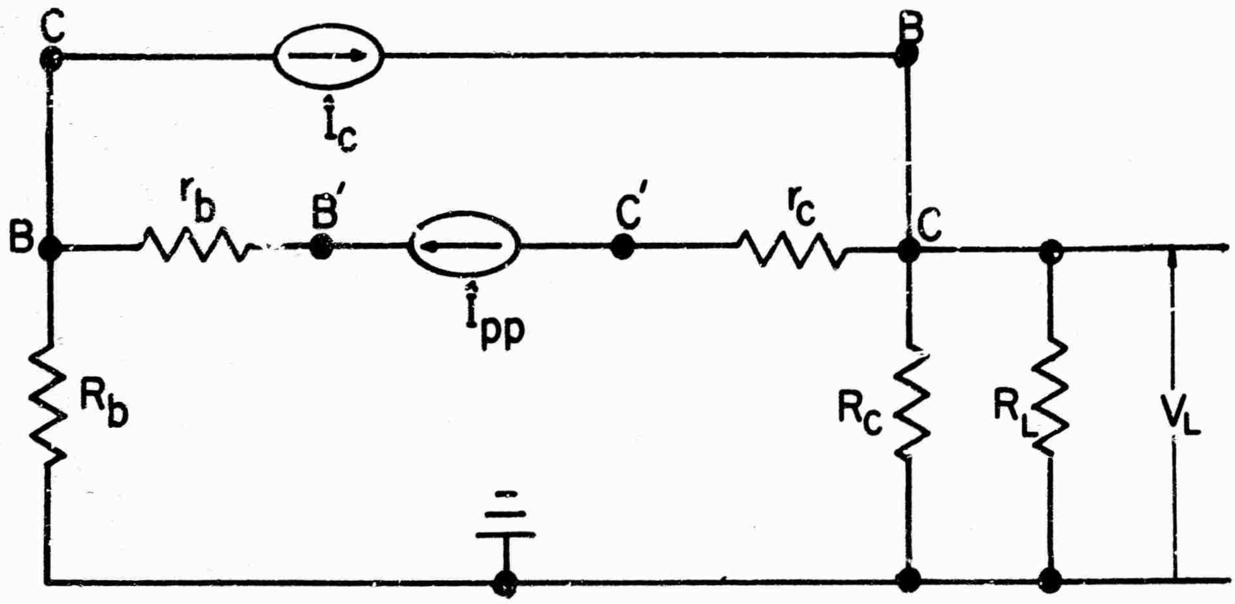


Figure 13. Cutoff Region ac Equivalent Circuit for Common-Emitter Amplifier with Collector-to-Base Cancellation

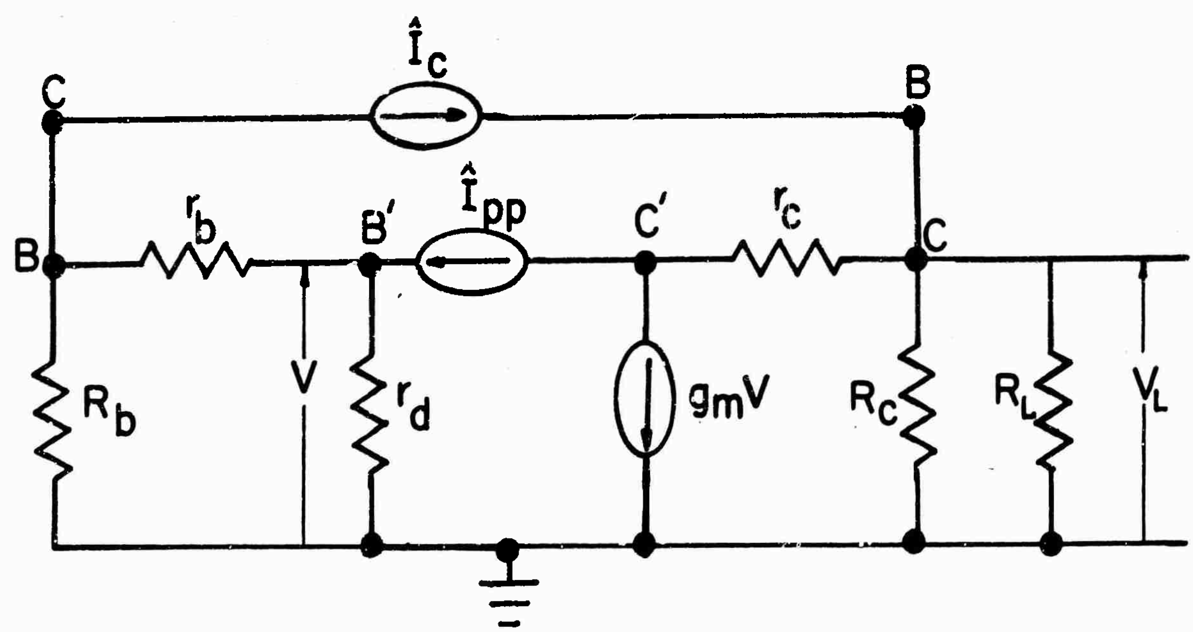


Figure 14. Active Region ac Equivalent Circuit for Common-Emitter Amplifier with Collector-to-Base Cancellation

For cancellation, make

$$\hat{I}_c \doteq \left[1 + \frac{\beta}{1+\beta}\frac{r_b}{R_b}\right]\hat{I}_{pp} \doteq \hat{I}_{pp} \qquad (21)$$

<u>Saturation Region</u>. The saturation region equivalent circuit is shown in figure 15. The peak pulse output voltage is

$$V_L \doteq \hat{I}_c \; R_c \| R_L \| r_c \qquad (22)$$

The value of r_c is normally quite small compared to R_c or R_L, and hence, the output pulse is small for saturation. In actual practice there is no abrupt change from the active to the saturation regions but rather a smooth decrease in the output pulse as saturation is approached by increasing the input bias voltage, V_b.

In summary (considering all regions of operation), for the common-emitter amplifier using collector-to-base compensation, make

$$\hat{I}_c \doteq \hat{I}_{pp} \qquad (23)$$

For identical T1 and T2 junctions, this can be achieved by making

$$V_{xj} = V_x - V_c \doteq V_c - V_{BE} = V_{CB} \qquad (24)$$

since for $V_{xj} \doteq V_{CB}$, $\hat{I}_c \doteq \hat{I}_{pp}$. Note, from equation (24), that for operation from the midactive to the saturation region, it is possible to get the V_x voltage from the V_{cc} supply directly by use of suitable voltage dividers.

b. Base-to-Ground Compensation. Another method of achieving junction compensation in the common-emitter amplifier is to have a properly back-biased junction between the active transistor base and ground. Referring to figure 16, the collector-to-base junction of T2 is used as the compensation junction. In this case, the compensation junction voltage V_{xj} is just V_x and the active-device junction voltage ~~is~~ $V_c - V_{BE}$. Referring t the equivalent circuit shown in figure 17, the equation for $V_{B'E}$ is the same as for collector-to-base compensation (equation 15), and the criterion for assuring operation in the cutoff region is also the same (equation 16).

Cutoff-Region Analysis. For the cutoff region of operation, the compensation is effective in keeping the radiation from pushing the amplifier into the active region, but no compensation effect is present in the output circuit. Thus, no way is available to cancel out the unamplified primary photocurrent, I_{pp}, which flows through the equivalent ac load resistance. For the cutoff mode, the resulting pulse output is given by

$$V_L \doteq - \hat{I}_{pp} R_c \| R_L \tag{25}$$

Active-Region Analysis. The equation for the peak pulse output is given by

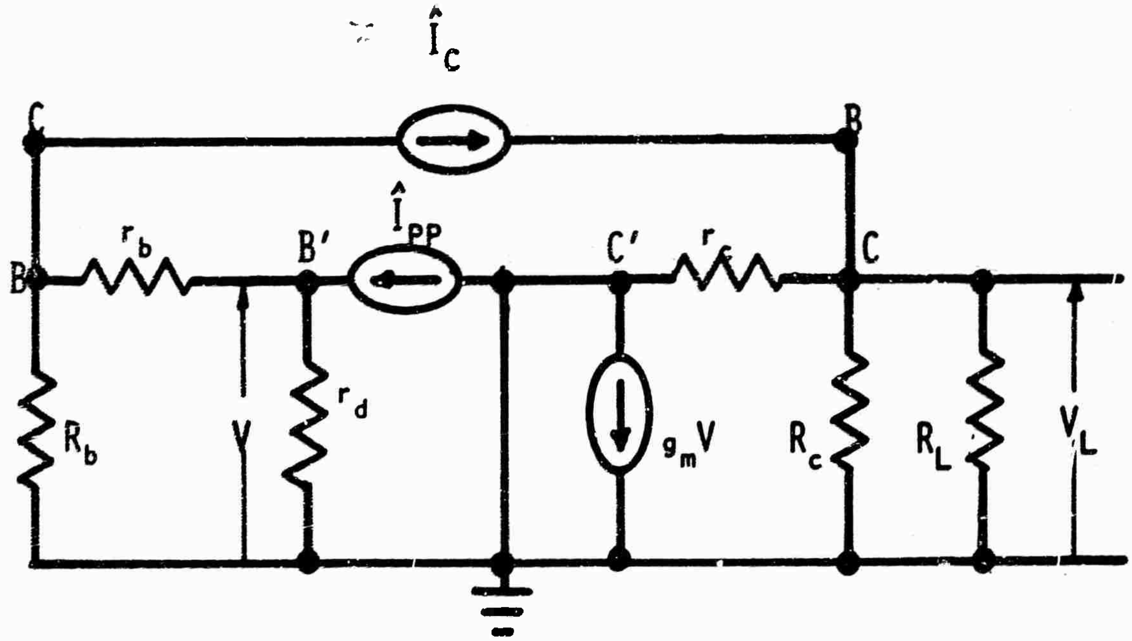


Figure 15. Saturation Region ac Equivalent Circuit for Common-Emitter Amplifier with Collector-to-Base Cancellation

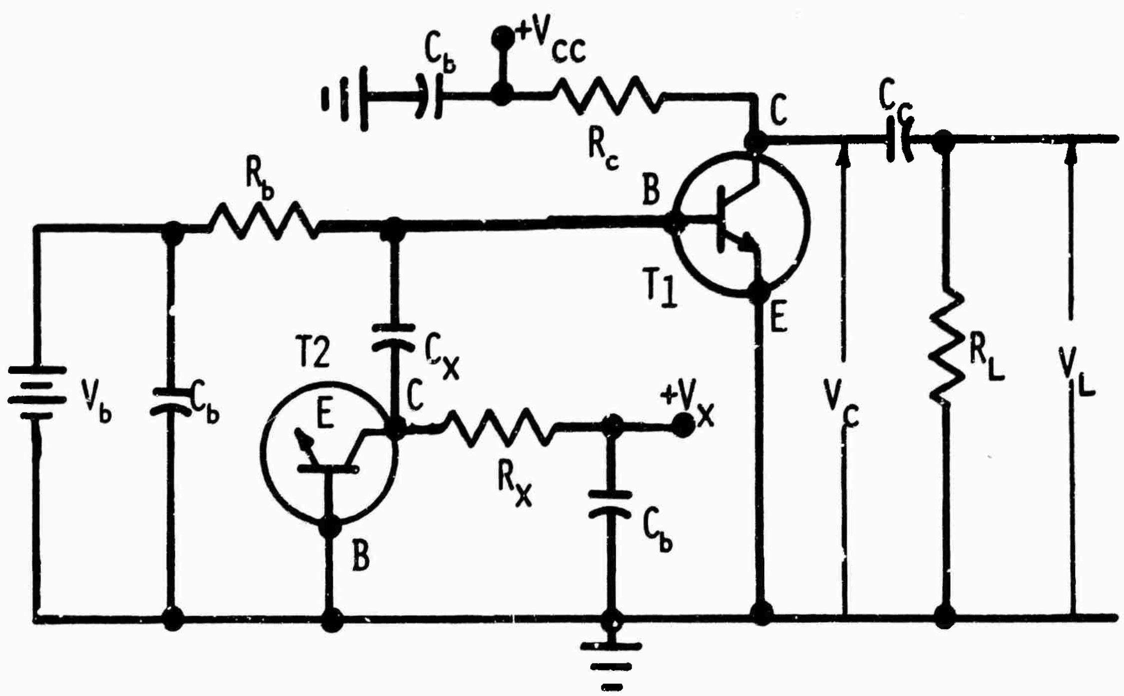


Figure 16. Circuit for Common-Emitter Amplifier with Base-to-Ground Cancellation

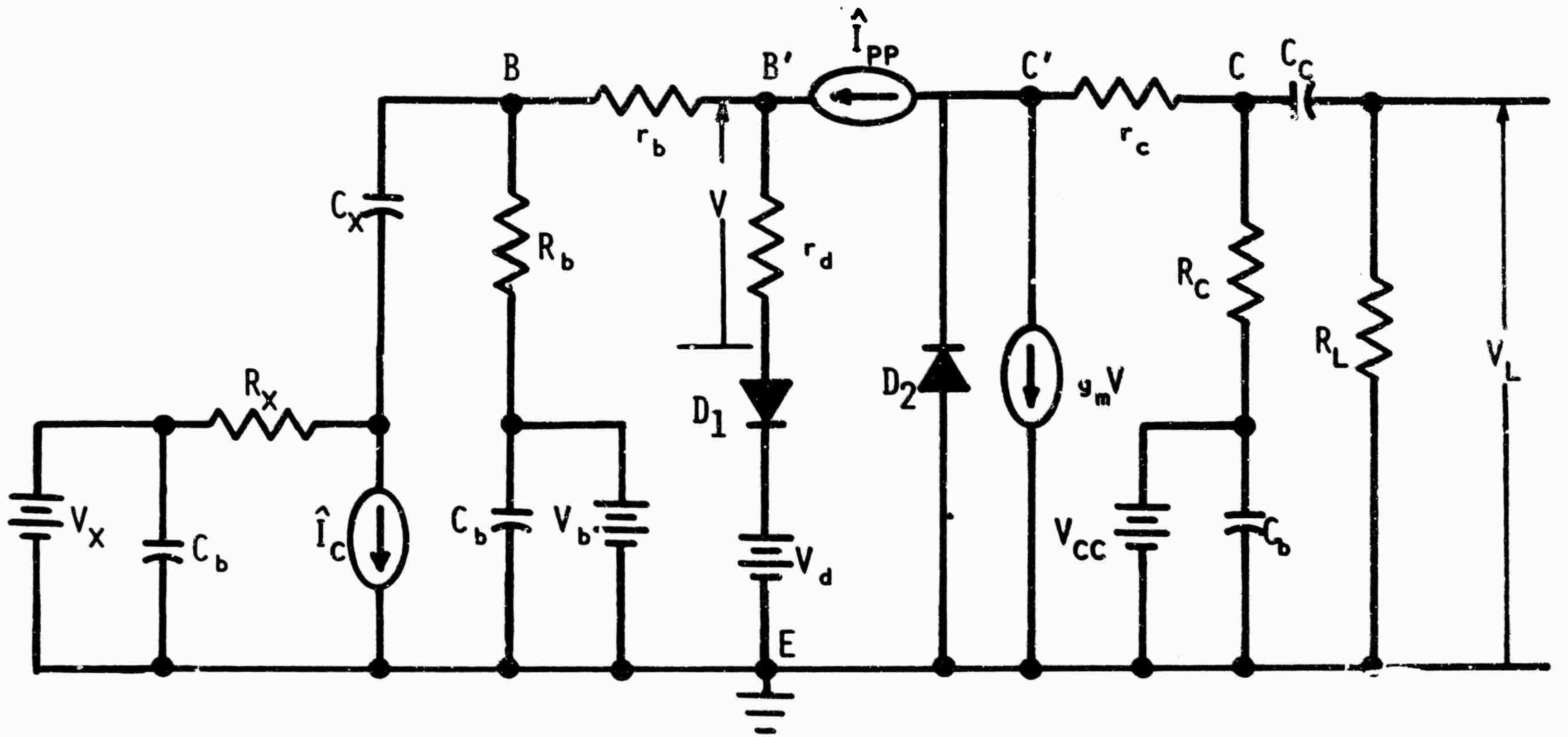


Figure 17. Equivalent Circuit for Common-Emitter Amplifier with Base-to-Ground Cancellation

$$V_L = \left[\beta \frac{(R_b\hat{I}_c) - (R_b+r_b)\hat{I}_{pp}}{R_b + r_b + r_d} - \hat{I}_{pp}\right] R_c \| R_L \tag{26}$$

If we assume $R_b >> r_b + r_d$,

$$V_L \doteq \left[\beta \hat{I}_c - (1 + \beta) \hat{I}_{pp}\right] R_c \| R_L \tag{27}$$

The relationship required to achieve cancellation is that we make

$$\hat{I}_c \doteq (\frac{1}{\beta} + 1) \hat{I}_{pp} \tag{28}$$

<u>Saturation-Region Analysis</u>. For the heavily saturated region of operation, the pulse output should (within the limitations of the model) be essentially zero.

In summary, for this cancellation technique, $\hat{I}_c$ should be slightly larger than $\hat{I}_{pp}$ to achieve best cancellation (equation 28). Also note that for operation near saturation, it should be possible to place a compensation junction from the base of T1 to ground without any V_x bias voltage being necessary. For this method, the collector of T2 is tied directly to the base of T1, and the base of T2 is connected to ground. The requirement is still that $\hat{I}_c$ be slightly larger than $\hat{I}_{pp}$. For identical junctions, this limits the operation to near-saturation because of the requirement that the active and compensation junctions have approximately the same voltage across them. However, if two different types of junction are used that have the required radiation

responses, correct cancellation should be possible for other regions of operation without the requirement that the two junction voltages be approximately the same.

c. Collector Output-to-Ground Compensation

It appears theoretically possible (but was not experimentally verified) that compensation can be achieved by placing a back-biased junction from the collector output to ac ground. Two methods of doing this conveniently are shown in figure 18. For one method, T2 is used as the compensation junction, with the voltage supplied from an external source, V_x. For the other method, T3 is used, and connection is made beyond the coupling capacitor, C_c, directly to the V_{cc} power supply. The two methods are equivalent for ac or pulse operation, and the basis for choice is associated with factors such as the quiescent operating point or the characteristics of the junctions. Considerable design spread is available between the two junction voltages, which are respectively, for T2 and T3,

$$V_{xj2} = V_x - V_c \tag{29}$$

and

$$V_{xj3} = V_{cc} \tag{30}$$

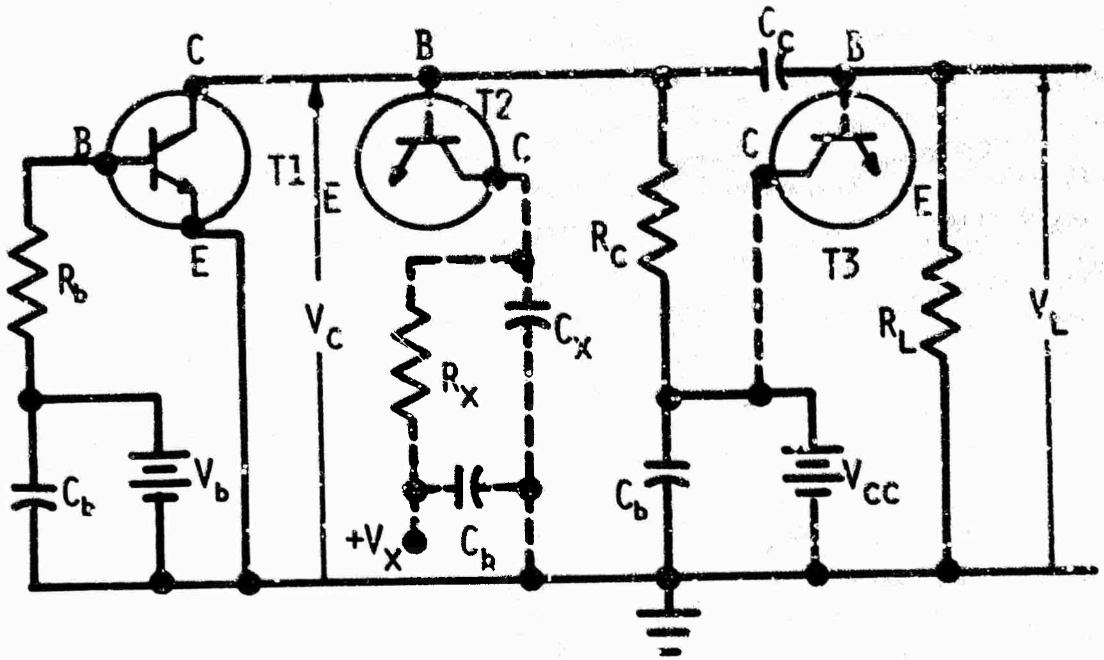


Figure 18. Circuit for Common-Emitter Amplifier with Collector Output-to-ac-Ground Cancellation

The ac equivalent circuit (applicable for either T2 or T3) is shown in figure 19. For this type of compensation, no current-cancellation effect occurs in the input circuit, and one normally expects the amplifier (while in the cutoff mode) to be pushed into the active region of operation during irradiation. To force the amplifier to stay cut off during irradiation, it is usually necessary to make V_b negative to keep $V_{B'E} < V_d$. The requirement on V_b to achieve this is

$$V_b < V_d - (r_b + R_b \| R_s)\hat{I}_{pp} , \qquad (31)$$

where R_s is the equivalent series resistance of a signal source which is capacitively coupled to the base of the transistor T1. However, as V_b is made more negative, the required amplitude of the signal voltage is increased.

Cutoff Region. If one assumed that the requirements of equation (31) are met and that the unit thus stays cut off the expression for the peak voltage output is

$$V_L \doteq (\hat{I}_c - \hat{I}_{pp}) R_c \| R_L . \qquad (32)$$

For proper compensation, make $\hat{I}_c \doteq \hat{I}_{pp}$.

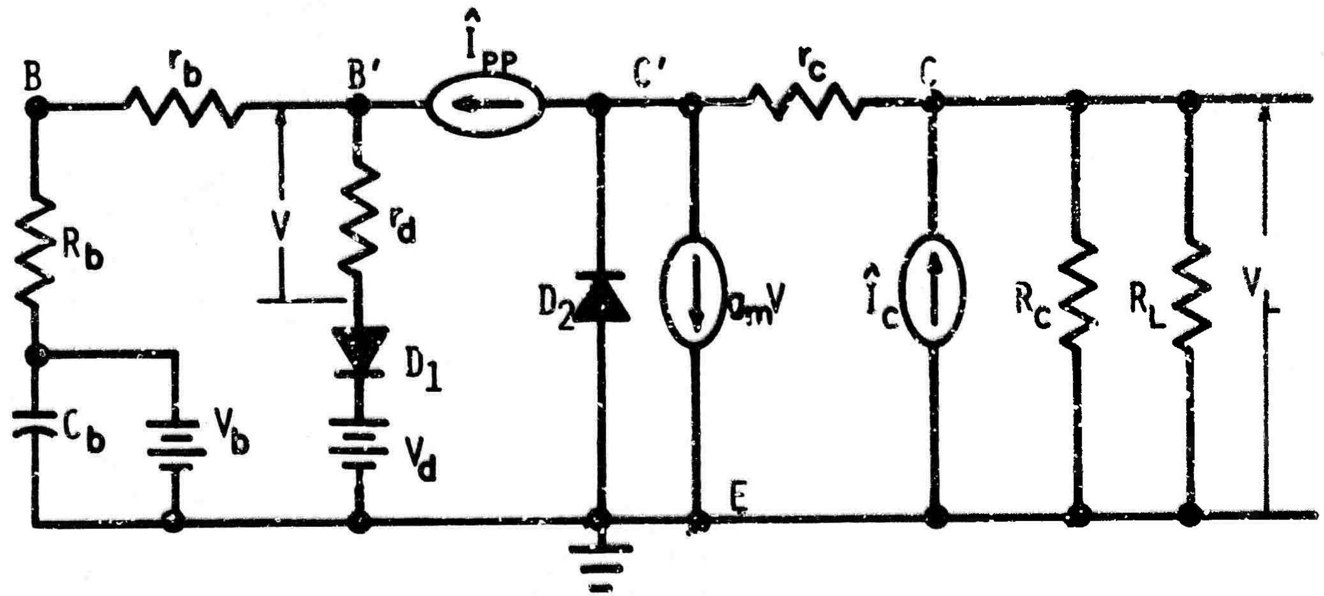


Figure 19. Equivalent Circuit for Common-Emitter Amplifier with Collector Output-to-ac-Ground Cancellation

Active Region. Within the active region of operation, the primary photocurrent, I_{pp}, produces large secondary photocurrents because no compensation effect is operating in the base-emitter circuit of T1. To achieve compensation, it is thus necessary that $\hat{I}_c$ be large compared to $\hat{I}_{pp}$. This is shown by the equations for the peak of the output voltage

$$V_L = \left[\hat{I}_c - \hat{I}_{pp} - g_m V\right] R_c \| R_L \doteq \left[\hat{I}_c - (1+\beta)\hat{I}_{pp}\right] R_c \| R_L \quad (33)$$

where

$$g_m V = \beta \, \hat{I}_{pp} \, \frac{R_b + r_b}{R_b + r_b + r_d} \doteq \beta \, \hat{I}_{pp} \quad (34)$$

for $R_b + r_b >> r_d$. Thus, for proper compensation it is required that

$$\hat{I}_c \doteq (1+\beta) \, \hat{I}_{pp} \quad (35)$$

Using quality transistors, for the usual values of β this required ratio of $\hat{I}_c$ to $\hat{I}_{pp}$ is too large to be obtained by strictly varying the depletion component of identical junctions. Two different types of junction with varying areas and/or doping must be used to obtain the necessary radiation photocurrent response. For this reason, the design of a circuit using the collector-to-ground compensation technique is more difficult than the other approaches discussed.

5. Junction Compensation Techniques for Radiation Hardening of the Common-Base Amplifier

An approximate large-signal equivalent circuit for the n-p-n transistor common-base configuration was developed in section III-3. This circuit is now used to analyze a number of different approaches for hardening the common-base amplifier and to evolve the necessary circuit criteria.

As in the previous subsection, the cutoff, active and saturation regions of operation are considered.

a. Collector Output-to-Ground Compensation. The first method of hardening the common-base amplifier considered is the use of a compensation junction from the collector output to the ac ground. The dc biasing of this added junction may be accomplished in a number of ways. The method adopted depends upon practical design considerations such as the desired bias region of operation and the available source voltages.

In figure 20, three methods of placing back-biased junctions from the collector output to ac ground are shown. The added junctions involved are T2, T3, and T4. In any of these cases, the collector-to-base junction voltage, V_{CB}, of the active device, T1, is just V_c, the quiescent collector voltage. Normally, if the active device and the compensation junction used are the same, the method of obtaining the required ratio of $\hat{I}_{pp}$ to $\hat{I}_c$ is by varying the depletion

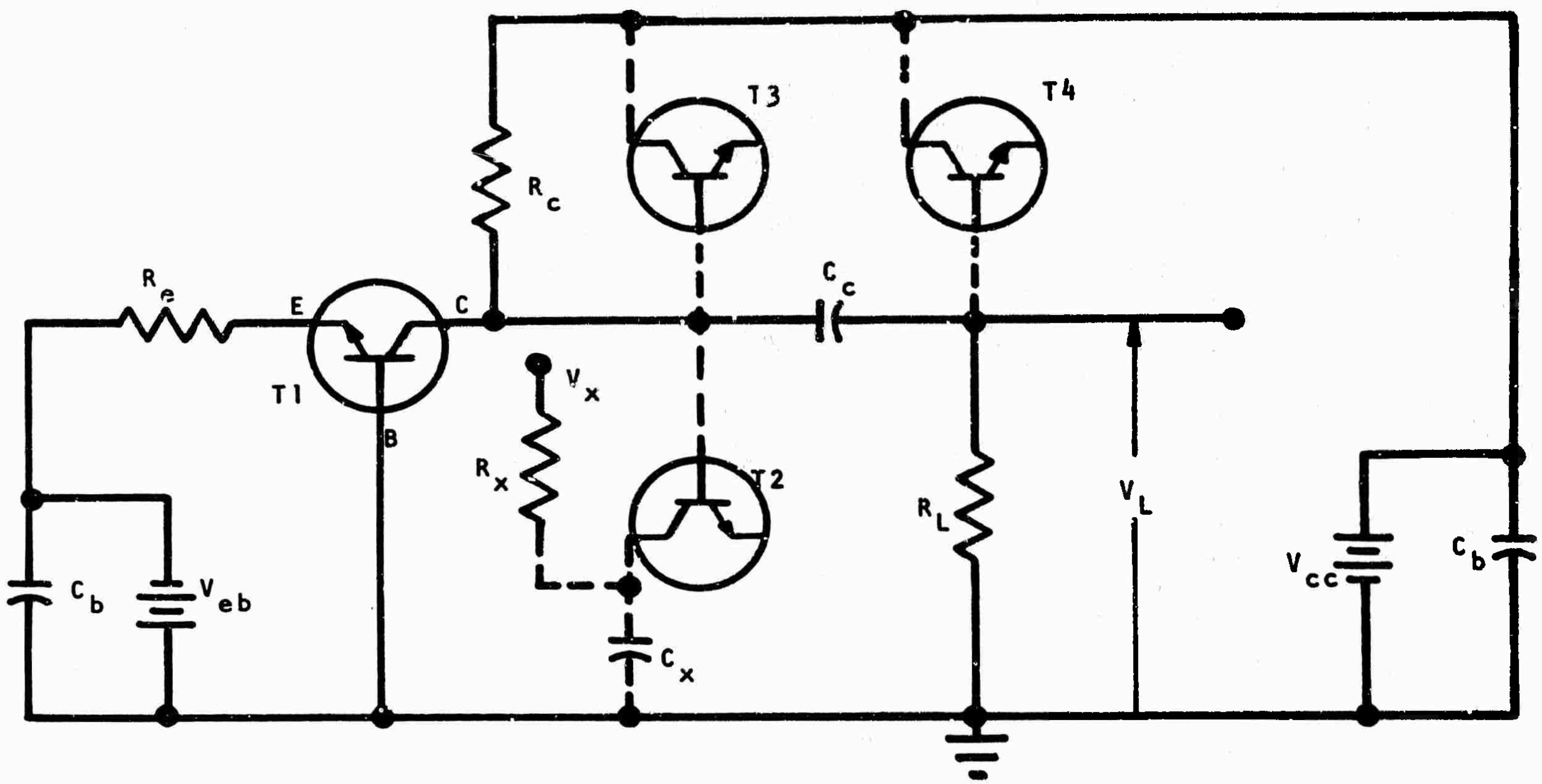


Figure 20. Circuit for Common-Base Amplifier with Methods for Collector Output-to-Ground Compensation

component of $\hat{I}_c$. This is done by varying the junction voltage. The three methods shown are completely equivalent on a pulse basis; only the dc voltages are different. These methods are as follows:

Use of T2. This method is of general interest, as the V_{xj} voltage can be made any value required. It is

$$V_{xj2} = V_x - V_c \tag{36}$$

Use of T3. No added components other than T3 are required in this method, and the resulting junction voltage is

$$V_{xj3} = V_{cc} - V_c \tag{37}$$

Use of T4. This also requires no extra components. The resulting junction voltage is

$$V_{xj4} = V_{cc} - V_L(dc) \tag{38}$$

On a pulse or ac basis, the equivalent circuit is the same for all three of the above approaches. Figure 21 shows an equivalent circuit for the common-base amplifier with collector-to-ground compensation. The peak of the compensation junction primary photocurrent is $\hat{I}_c$. All operating regions for T1 can be approximately accounted for by the action of the ideal diodes D_1 and D_2. The transistor is cut off when D_1 is not conducting; it is in saturation when

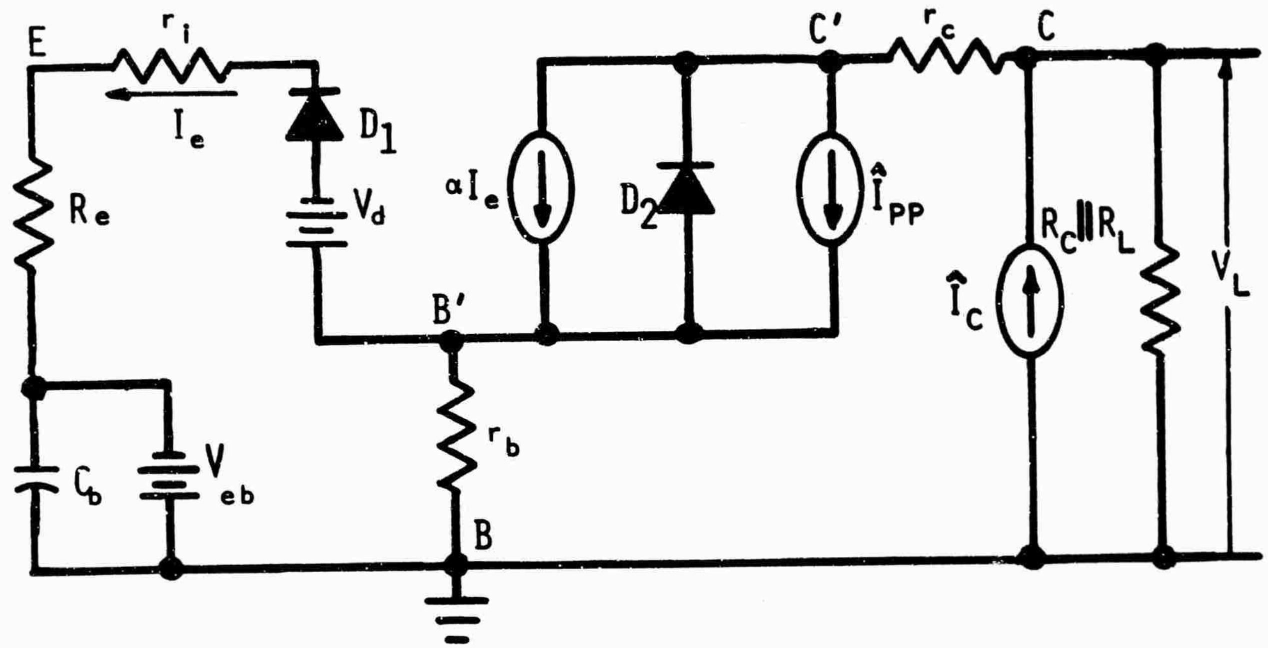


Figure 21. Equivalent Circuit for Common-Base Amplifier with Collector Output-to-Ground Compensation

D_2 is conducting. The transistor is cut off for $V_{EB'} > -V_d$; it is saturated for $V_{C'B'} < 0$. Thus, the equations defining the active region of operation are

$$V_{EB'} \leq -V_d \text{ and } V_{C'B'} \geq 0 \tag{39}$$

Cutoff Region. For cutoff, we must have $V_{EB'} > -V_d$. Assuming that the amplifier is cut off $I_e = 0$; hence,

$V_{B'B} = r_b \hat{I}_{pp}$.

Thus,

$$V_{EB'} = V_{eb} - r_b \hat{I}_{pp} > -V_d \tag{40}$$

or

$$V_{eb} > r_b \hat{I}_{pp} - V_d \tag{41}$$

is the relationship required for the amplifier to remain cut off during irradiation. It may be necessary to make V_{eb} slightly positive, if it is critical that the amplifier remain cut off.

Assuming that the amplifier does remain cut off, the peak value of the output voltage is

$$V_L = \left[\hat{I}_c - \hat{I}_{pp}\right] R_c \| R_L \quad , \tag{42}$$

Then,

$$\hat{I}_c \doteq \hat{I}_{pp} \tag{43}$$

for proper compensation. Now, in cutoff $V_{CB} = V_{cc}$ and $V_{xj4} \doteq V_{cc}$. Thus, for the cutoff region, the use of compensation T4 may be convenient.

<u>Active Region</u>. In the active region of operation, I_e is no longer zero and the equation for the peak of the output voltage becomes

$$V_L = \left[\hat{I}_c - \hat{I}_{pp} - \alpha I_e \right] R_c \| R_L \qquad (44)$$

where

$$\alpha I_e = \frac{\alpha r_b \hat{I}_{pp}}{R_e + r_i + (1-\alpha) r_b} \qquad (45)$$

For cancellation,

$$\hat{I}_c = \left[1 + \frac{\alpha r_b}{R_e + r_i + (1-\alpha) r_b}\right]\hat{I}_{pp} \doteq \left[1 + \frac{r_b}{R_e + r_i}\right]\hat{I}_{pp} \qquad (46)$$

for $\alpha \doteq 1$.

<u>Saturation Region</u>. In saturation, D_2 conducts and

$$V_L \doteq \hat{I}_c \cdot R_c \| R_L \| \left[r_c + r_b \| (r_i + R_e)\right] \qquad (47)$$

In this region, the output becomes so small that compensation is not really of any help.

b. <u>Emitter-to-Ground Compensation</u>. The next method of hardening the common-base amplifier discussed is the use of a back-biased junction from the emitter to ground as shown in figure 22. Shown is a biasing arrangement for V_x. For certain applications, it may be possible to eliminate V_x, R_x, and C_x and simply connect the collector of T2 directly to ground. In this case, the compensation junction voltage is just V_{BE}.

The pulse equivalent circuit for this method of compensation is shown in figure 23, where $\hat{I}_c$ is the primary photocurrent from the compensation junction.

<u>Cutoff Region</u>. To keep the circuit in cutoff, have $V_{EB'} > -V_d$. If the amplifier remains cut off during irradiation, I_e is zero; hence, $V_{B'B} = r_b \hat{I}_{pp}$. The voltage

$$V_{EB'} = V_{eb} + \hat{I}_c R_e - r_b \hat{I}_{pp} > -V_d \tag{48}$$

requirement implies that one make

$$V_{eb} > -V_d + r_b \hat{I}_{pp} - \hat{I}_c R_e \tag{49}$$

to assure remaining in cutoff during irradiation. Note from equation (49) that $\hat{I}_c$, the compensation current, is tending to keep the transistor in cutoff. For cutoff, the output voltage is

$$V_L = -\hat{I}_{pp} R_c \| R_L \tag{50}$$

and no compensation effect is present in the output circuit.

<u>Active Region</u>. I_e is no longer zero; it has a value of

$$I_e = \frac{r_b \hat{I}_{pp} - R_e \hat{I}_c}{R_e + r_i + (1-\alpha) r_b} \tag{51}$$

The output voltage then is given by

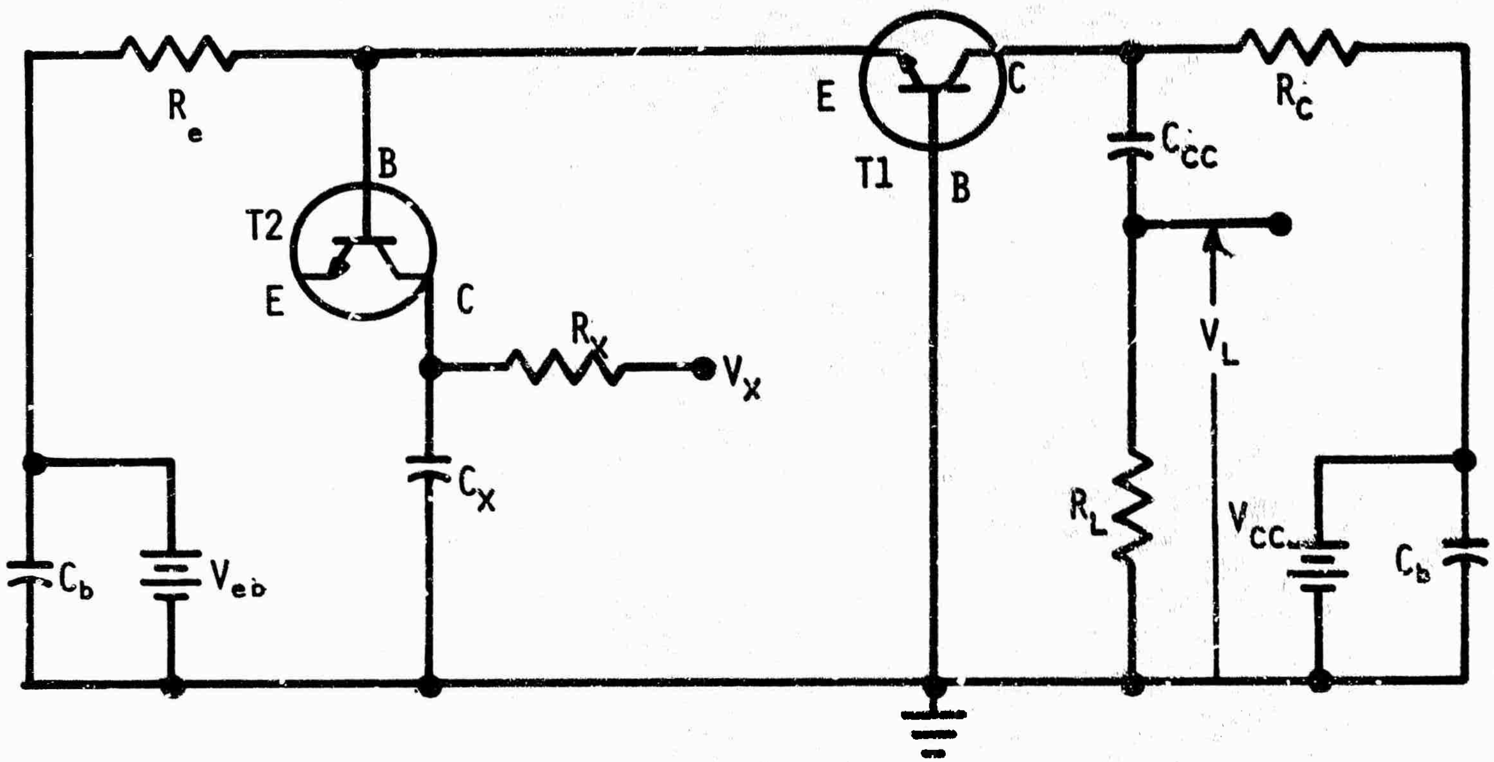


Figure 22. Circuit for Common-Base Amplifier with Emitter-to-Ground Compensation

$$V_L = -\left[\hat{I}_{pp} + \frac{\alpha r_b \hat{I}_{pp} - \alpha R_e \hat{I}_c}{R_e + r_i + (1-\alpha) r_b}\right] R_c \| R_L \tag{52}$$

or

$$V_L \doteq -\left[I_{pp} + \frac{r_b \hat{I}_{pp} - R_e \hat{I}_c}{R_e + r_i}\right] R_c \| R_L \tag{53}$$

for $\alpha \doteq 1$. The requirement for cancellation in the output then is

$$\hat{I}_c \doteq \left[1 + \frac{r_i + r_b}{R_e}\right] \hat{I}_{pp} \tag{54}$$

Normally, R_e is comparable in value to $r_i + r_b$. Thus, $\hat{I}_c$ usually would not have to be so much larger than $\hat{I}_{pp}$ that identical junctions for T1 and T2 could not be used.

<u>Saturation Region</u>. For the saturation region operation, the output is essentially zero within the limitations of the equivalent circuit used.

c. <u>Collector-to-Emitter Compensation</u>. Another possible method of hardening the common-base amplifier is shown in figure 24. A compensation junction, T2, is connected between the collector and emitter of T1 with a V_x source voltage as indicated. The resulting compensation junction voltage is $V_{xj} = V_x - V_c$.

<u>Cutoff Region</u>. As shown by the equivalent circuit in figure 25, the compensation current, $\hat{I}_c$, tends to turn the transistor on. To keep the circuit in cutoff during irradiation, it is necessary that V_{eb} be positive and of value

$$V_{eb} > - V_d + r_b \hat{I}_{pp} + R_e \hat{I}_c \tag{55}$$

Assuming that the unit remains in cutoff, the output pulse peak is

$$V_L = [\hat{I}_c - \hat{I}_{pp}] R_c \| R_L \tag{56}$$

Make $\hat{I}_c \doteq \hat{I}_{pp}$ to achieve compensation.

Active Region. In the active region of operation, cancellation is achieved by greatly overcompensating the output circuit. I_e is given by

$$I_e = \frac{r_b \hat{I}_{pp} + R_e \hat{I}_c}{R_e + r_i + (1-\alpha) r_b} \tag{57}$$

and

$$V_L = [\hat{I}_c - \hat{I}_{pp} - \alpha I_e] R_c \| R_L \tag{58}$$

For proper compensation, make

$$\hat{I}_c = \frac{r_i + R_e + r_b}{r_i + (1-\alpha)(r_b + R_e)} \hat{I}_{pp} \doteq \left[1 + \frac{R_e + r_b}{r_i}\right] \hat{I}_{pp} \tag{59}$$

for $\alpha \doteq 1$. Equation (59) shows that $\hat{I}_c$ has to be considerably larger than $\hat{I}_{pp}$. For this reason, the collector-to-emmitter compensation is not a preferred approach for hardening of the common-base amplifier.

Saturation Region. In saturation, the output is

$$V_L = \hat{I}_c \frac{\Sigma}{r_b} \frac{R_c \| R_L \| \frac{\Sigma}{r_i}}{\frac{\Sigma}{r_b} + R_e \| \frac{\Sigma}{r_c} + R_c \| R_L \| \frac{\Sigma}{r_i}} \tag{60}$$

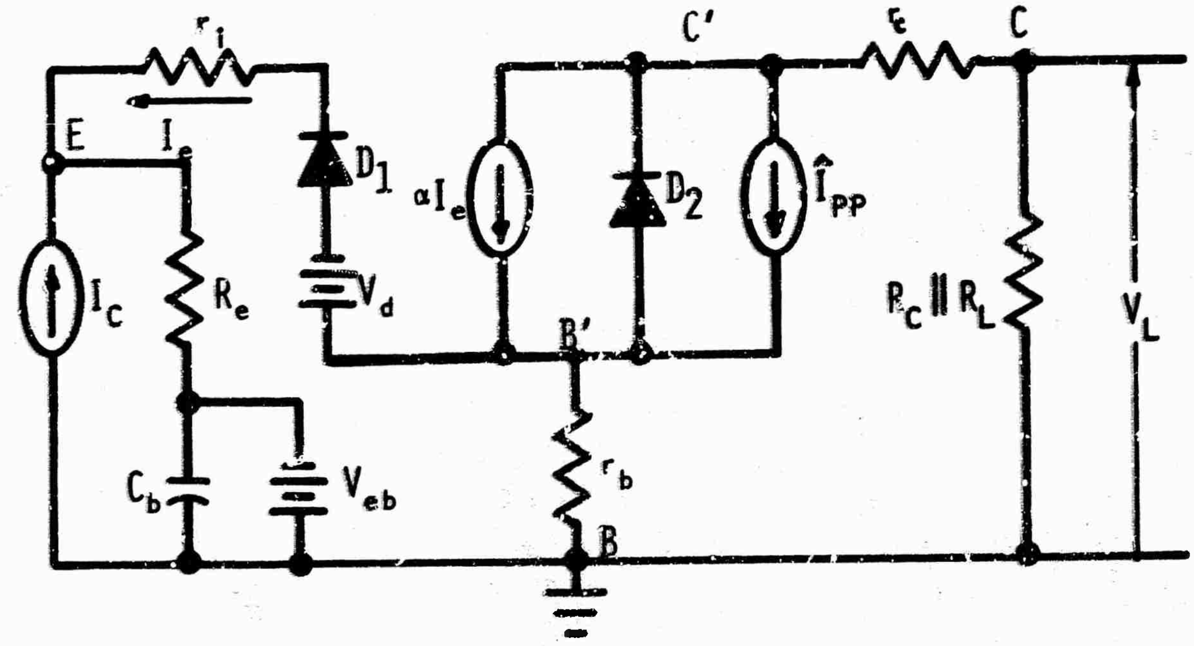


Figure 23. Equivalent Circuit for the Common-Base Amplifier with Emitter-to-Ground Compensation

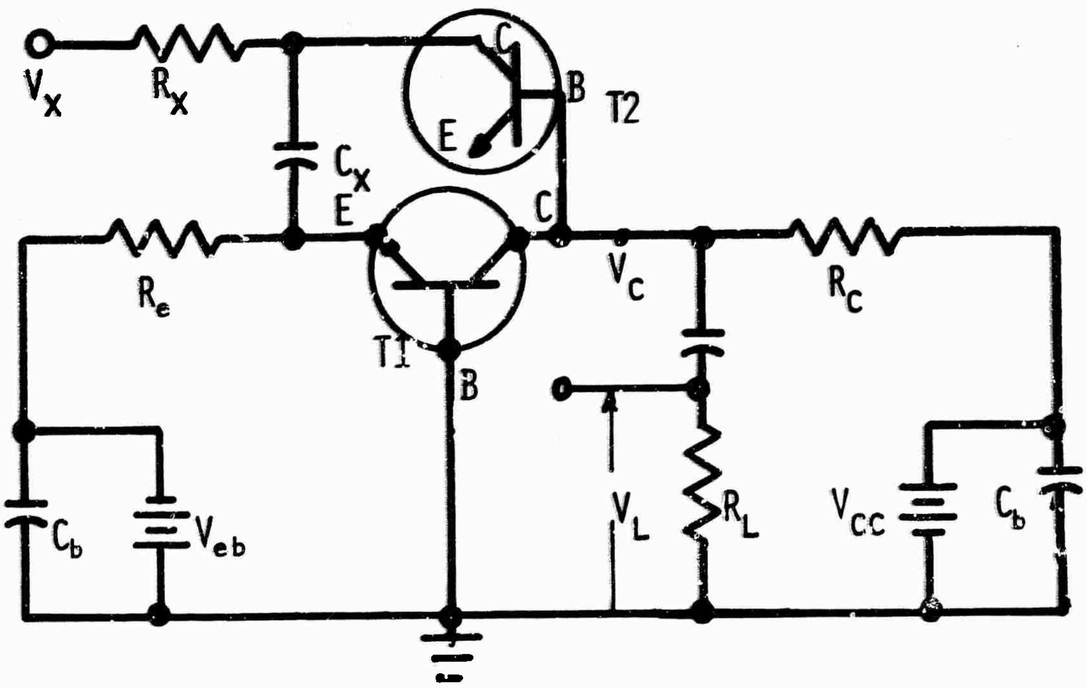


Figure 24. Circuit for Common-Base Amplifier with Collector-to-Emitter Compensation

where

$$\Sigma = r_i r_c + r_c r_b + r_b r_i \quad .$$

Normally, the values of r_i, r_c, and r_b are small enough that the output given by equation (60) is negligible.

6. Junction-Compensation Techniques for Radiation Hardening of the Common-Collector (or Emitter-Follower) Amplifier

In section III-2, a large-signal equivalent circuit is developed for the n-p-n common-collector or emitter-follower amplifier. This approximate model is used to determine the criteria for hardening this amplifier against transient radiation. A number of basic junction compensation techniques are analyzed and different methods of achieving proper junction-biasing are discussed.

Cutoff, active, and saturation modes of operation are covered, under the assumption that proper biasing and/or compensation techniques prohibit the radiation from forcing the amplifier out of its original quiescent operating region.

a. Base-to-ac-Ground Compensation. Among the possible ways of hardening the common-collector amplifier, the use of a properly back-biased compensation junction from the base of the active transistor to ac ground seems the most promising. From the dc-biasing standpoint, several methods of connecting the cancellation junction in the circuit are possible.

Three methods of connecting the back-biased junctions are shown in figure 26. The compensation junctions involved are T2, T3, and T4. For each method, the active device (T1) collector-to-base voltage is $V_{CB} = V_{cc} - V_{BE} - V_E$. As disucssed previously, the ratio of $\hat{I}_c$ to $\hat{I}_{pp}$ is usually controlled by varying the depletion component of $\hat{I}_c$; this is

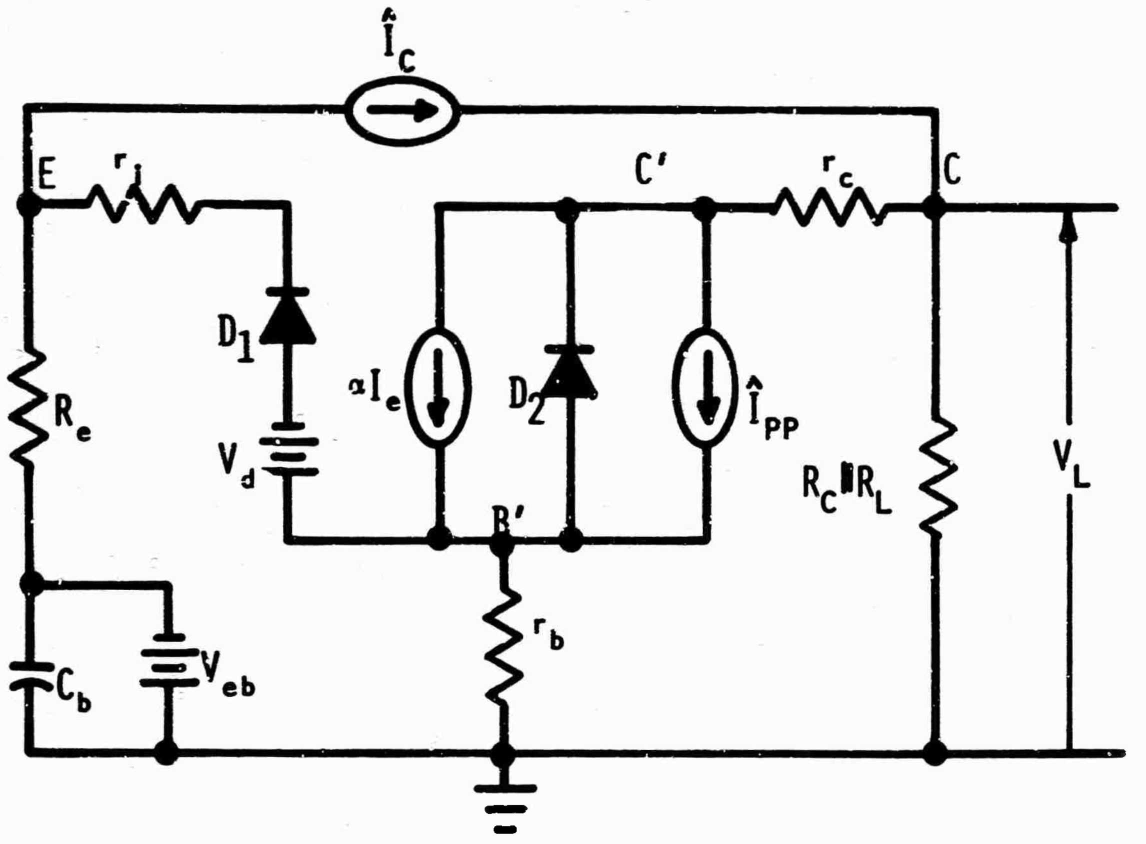


Figure 25. Equivalent Circuit for the Common-Base Amplifier with Collector-to-Emitter Compensation

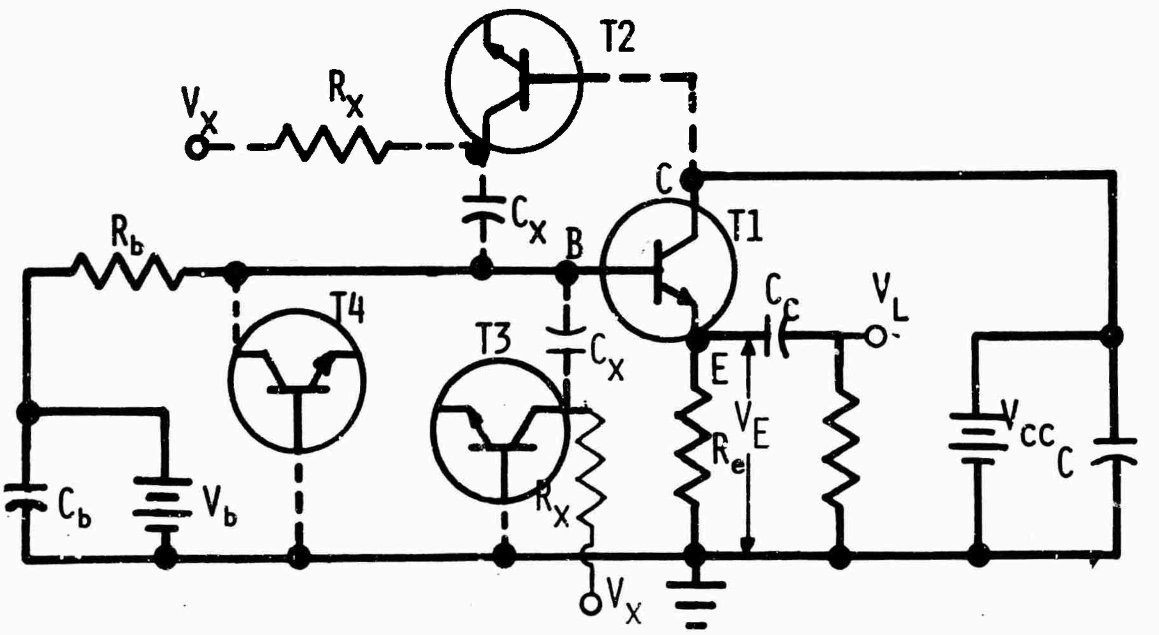


Figure 26. Circuit for Common-Collector Amplifier with Base-to-ac-Ground Compensation Methods

achieved by varying the junction voltage. Three compensation methods are shown; each has a different junction bias. The method used depends on practical design information such as the desired region of operation and the source voltages available. The bias methods for the circuits are as follows.

Use of T2. This approach is generally useful because of the V_x source voltage. However, V_x always has to be greater than V_{cc} to keep the compensation junction reverse-biased. The junction voltage is

$$V_{xj2} = V_x - V_{cc} \tag{61}$$

Use of T3. This is also generally useful because of the V_x voltage source which directly controls the V_{xj} voltage. If $V_x = V_{cc}$, compensation is obtained near the cutoff region of operation. The junction voltage is

$$V_{xj3} = V_x \tag{62}$$

Use of T4. This method is restricted in application. For identical junctions, proper compensation can be obtained only in the midactive to near-saturation region. However, the application is simple, requiring only the T4 junction. The junction voltage is

$$V_{xj4} = V_{BE} + V_E \tag{63}$$

The three methods are different in regard to dc voltages, but completely equivalent for short pulse operation. The equivalent circuit is the same for all three, for ac voltage or pulse-signal analysis. Figure 27 shows the equivalent circuit for the common-collector amplifier which is applicable for all three types of base-to-ac-ground compensation. The compensation photocurrent is indicated by $\hat{I}_c$. When D_1 is not conducting, the transistor is in the cutoff region; when D_2 conducts, the unit is saturated. Thus, the equations defining the active region of operation are

$$V_{B'E} \geq V_d \text{ and } V_{C'E} \geq 0 \tag{64}$$

<u>Cutoff Region.</u> In the cutoff mode of amplifier operation, $V_{B'E} < V_d$. Assuming cutoff,

$$V_{B'E} = [r_b + R_b]\,\hat{I}_{pp} + V_b - R_b\hat{I}_c < V_d \tag{65}$$

or

$$V_b < V_d + R_b\hat{I}_c - [r_b + R_b]\,\hat{I}_{pp} \tag{66}$$

Note, in equation (66), that the term $R_b\hat{I}_c$ tends to keep the radiation from turning the transistor on during irradiation, and thus, the requirements on V_b are considerably relaxed.

Assuming that the circuit remains cut off, the output voltage during irradiation is

$$V_L \doteq 0 \tag{67}$$

This mode of operation might be useful. The only requirement on $\hat{I}_c$ is that it be large enough to keep the amplifier cut off.

Active Region. V is no longer zero for the active region of operation and the peak value of the output voltage during irradiation is

$$V_L = \frac{(1+\beta)\left[(R_b+r_b)\ \hat{I}_{pp} - R_b\hat{I}_c\right] R_e \| R_L}{R_b+r_b+r_d+(1+\beta)\ R_e\|R_L} \tag{68}$$

and

$$\beta = g_m r_d \tag{69}$$

To achieve proper compensation, make

$$\hat{I}_c = (1 + \frac{r_b}{R_b})\ \hat{I}_{pp} \tag{70}$$

In the last equation, R_b is the external ac resistance as seen from the base.

Saturation Region. In saturation, D2 shorts out $g_m V$ and the output is

$$V_L = \frac{-\left[r_d\hat{I}_{pp}+R_b\hat{I}_c\right]R_e\|R_L\|r_c}{R_b+r_b+r_d+R_e\|R_L\|r_c} \tag{71}$$

Note that, in saturation, proper compensation is not achieved.

b. Output Circuit-to-Ground Compensation. The next basic method of hardening the common-collector amplifier to be analyzed is the use of a compensation junction from the output circuit (either at the V_e or V_L output point) to

ground. From the standpoint of dc-biasing, several ways of connecting the compensation junction in the amplifier may be used.

Three of the more obvious ways of connecting the back-biased junctions are shown in figure 28. The compensation junctions are the collector-to-base junctions of T2, T3, and T4. For each method, the collector-to-base voltage of the active device, T1, is $V_{CB} = V_{cc} - V_{BE} - V_E$.

All these methods of compensation require that $\hat{I}_c$ be considerably larger than $\hat{I}_{pp}$ to achieve compensation when the amplifier is operating in the active region. For this reason, the compensation junction must be different from the active device junction, and control of the magnitude of $\hat{I}_c$ will involve more than just the variation of the compensation junction voltage. However, for any junction selected, the circuit must be designed so that the junction voltage will have the required value. ~~The dc~~ levels for the circuits are as follows

<u>Use of T2</u>. Any value of compensation voltage desired may be had by varying V_x. The junction voltage is

$$V_{xj2} = V_x \tag{72}$$

<u>Use of T3</u>. This has restricted usefulness because the junction voltage is determined by the region of operation of the amplifier. However, no additional components are required other than the compensation junction. The junction voltage is

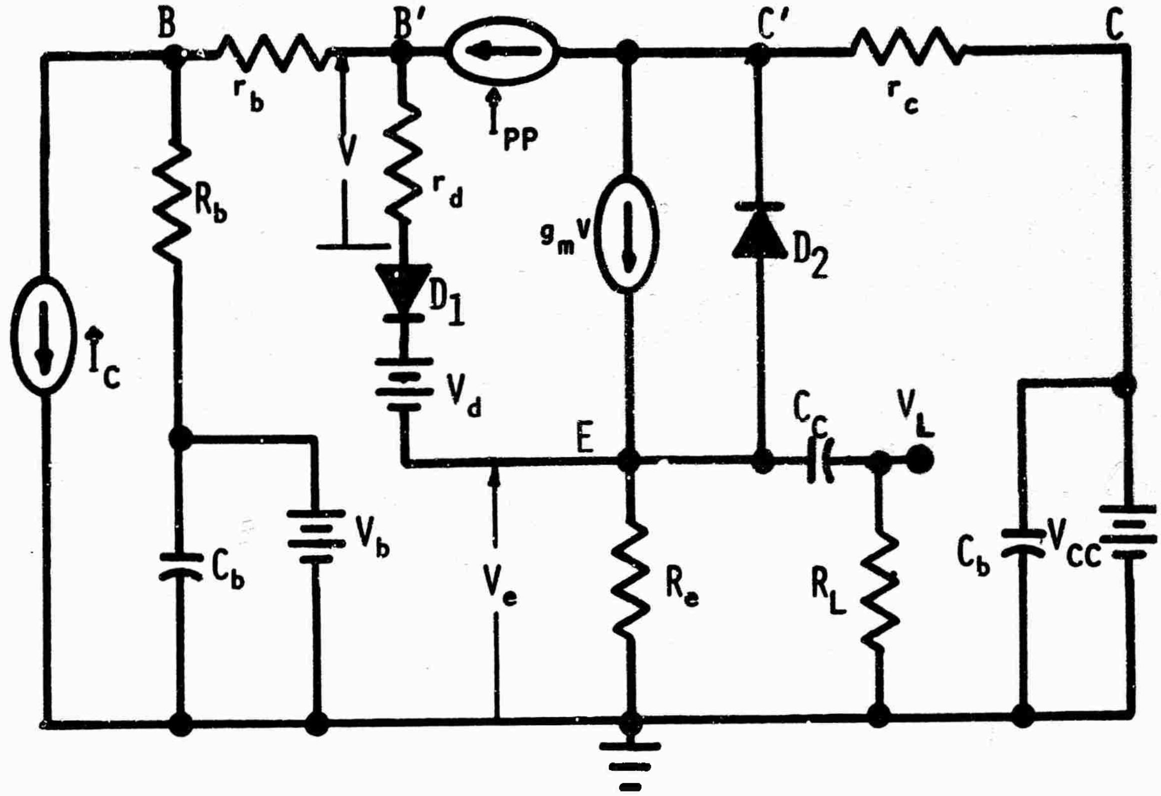


Figure 27. Equivalent Circuit for the Common-Collector (or Emitter-Follower) Amplifier with Base-to-ac-Ground Compensation

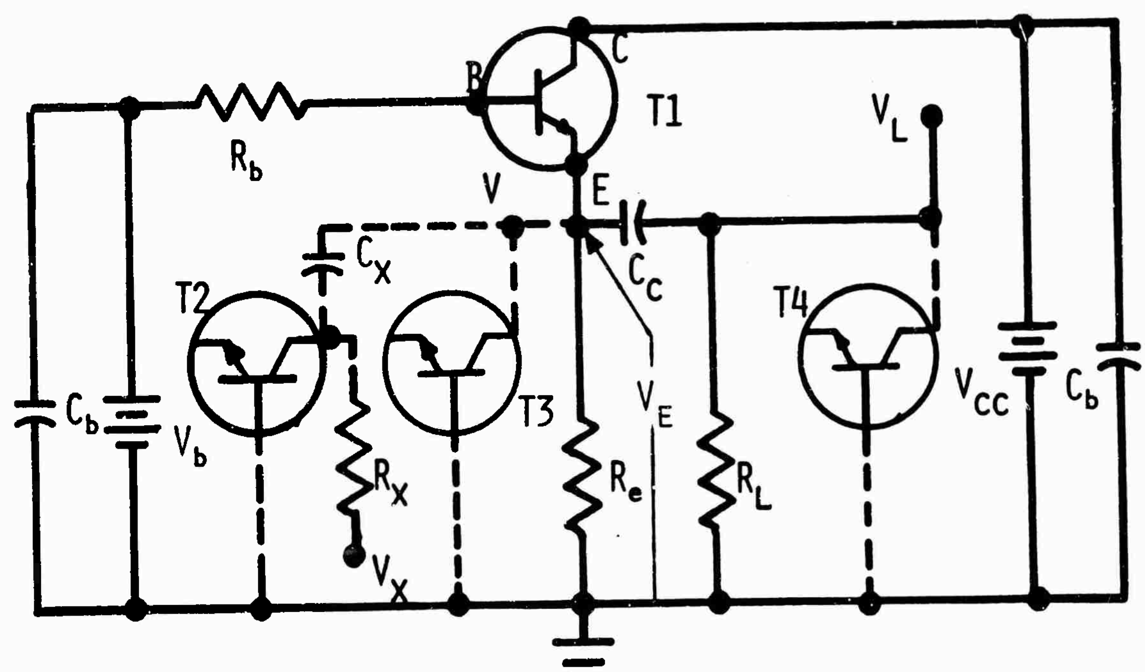


Figure 28. Circuit for the Common-Collector (or Emitter-Follower) Amplifier with Methods for Output Circuit-to-Ground Compensation

$$V_{xj3} = V_E \tag{73}$$

Use of T4. This method might be useful for certain applications where a positive dc level is present in the output due to voltages in the succeeding stage. The junction voltage is

$$V_{xj4} = V_L(dc) \tag{74}$$

All these methods are identical for short-pulse operation and the ac equivalent circuit is the same for each. The ac equivalent circuit is shown in figure 29. $\hat{I}_c$ is the peak of the compensation junction primary photocurrent.

Cutoff Region. For the circuit to remain in cutoff, it is necessary to have $V_{B'E} < V_d$. Under the assumption that the amplifier does remain cut off during irradiation, V is zero; hence, $V_e = - \hat{I}_c R_e \| R_L$. The voltage requirement for remaining in cutoff,

$$V_{B'E} = V_b + (R_b + r_b) \hat{I}_{pp} + \hat{I}_c R_e \| R_L < V_d \tag{75}$$

implies that one must make

$$V_b < V_d - (R_b + r_b) \hat{I}_{pp} - \hat{I}_c R_e \| R_L \tag{76}$$

Note, in equation (76), that the compensation current tends to turn the transistor on. Thus, it would probably be necessary that V_b be negative in order to force the transistor to remain cut off during irradiation. For cutoff operation, the peak of the output voltage is

$$V_L = - \hat{I}_c R_e \| R_L \tag{77}$$

Note that, for cutoff, the compensation junction increases the transient-radiation response, and hence, this technique should not be used for this mode of operation.

Active Region. In the active region of operation, V is no longer zero and secondary photocurrent generation occurs. The peak of the output voltage then becomes

$$V_L = \frac{(1+\beta)(R_b+r_b)\ \hat{I}_{pp} - (R_b+r_b+r_d)\ \hat{I}_c}{R_b+r_b+r_d+(1+\beta)\ R_e \| R_L} R_e \| R_L \tag{78}$$

To achieve proper compensation,

$$\hat{I}_c = (1+\beta)\frac{R_b+r_b}{R_b+r_b+r_d}\hat{I}_{pp} \doteq (1+\beta)\ \hat{I}_{pp} \tag{79}$$

for $R_b + r_b >> r_d$. Note that $\hat{I}_c$ must be considerably larger than $\hat{I}_{pp}$ for the usual values of β and that a special compensation junction design is necessary.

Saturation Region. The output pulse peak is

$$V_L = \frac{-(R_b+r_b+r_d)\hat{I}_c - r_d\ \hat{I}_{pp}}{r_d(r_b+R_b)\left[1+\frac{1}{r}(r_b+R_b+r_d)\right]} r_d(R_b+r_b) \tag{80}$$

where

$$r = r_c \| R_e \| R_L .$$

Note that no compensation effect is present during saturation-region operation.

c. Base-to-Emitter Compensation. Another compensation technique considered requires that a back-biased junction be added directly from the base to the emitter of the active device, T1. Two methods of achieving this are shown in

figure 30. T2 and T3 represent two different dc-bias arrangements as follows:

Use of T2. This method is limited in usefulness. The junction voltage is

$$V_{xj2} = V_{BE} \tag{81}$$

Use of T3. This method is of possible general usefulness, as the junction voltage can be made any value desired. The junction voltage is

$$V_{xj3} = V_x - V_e \tag{82}$$

Both these methods are identical for short-pulse operation, and an ac equivalent circuit is the same for both. The required equivalent circuit is shown in figure 31, where $\hat{I}_c$ is the peak value of the compensation junction primary photocurrent.

Cutoff Region. For this circuit to remain cut off, it is required that $V_{B'E} < V_d$. Assuming that the amplifier does remain cut off during irradiation, V is zero and $V_e = \hat{I}_c R_e \| R_L$. The voltage requirement for remaining in cutoff,

$$V_{B'E} = V_b + (R_b + r_b)\,\hat{I}_{pp} - \left[R_b + R_e \| R_L\right] \hat{I}_c < V_d \tag{83}$$

implies that one should make

$$V_b < V_d - (R_b + r_b)\,\hat{I}_{pp} + \left[R_b + R_e \| R_L\right] \hat{I}_c \tag{84}$$

Note, in equation (84), that the compensation current tends to help keep the unit in cutoff. Thus, it might even be

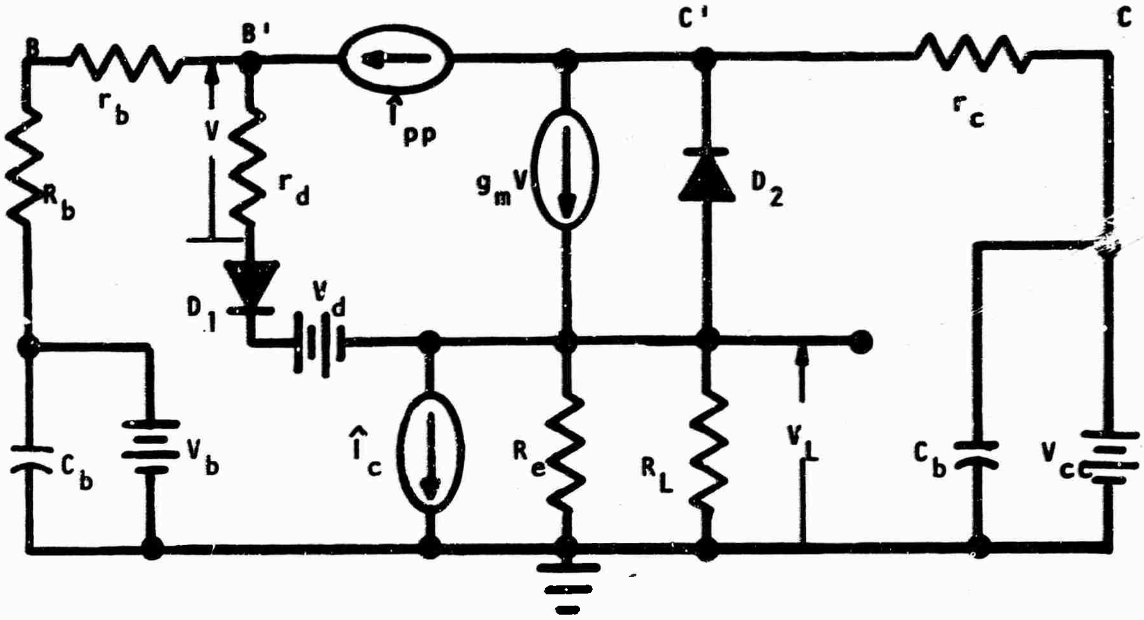


Figure 29. Equivalent Circuit for the Common-Collector (or Emitter-Follower) Amplifier with Output Circuit-to-Ground Compensation

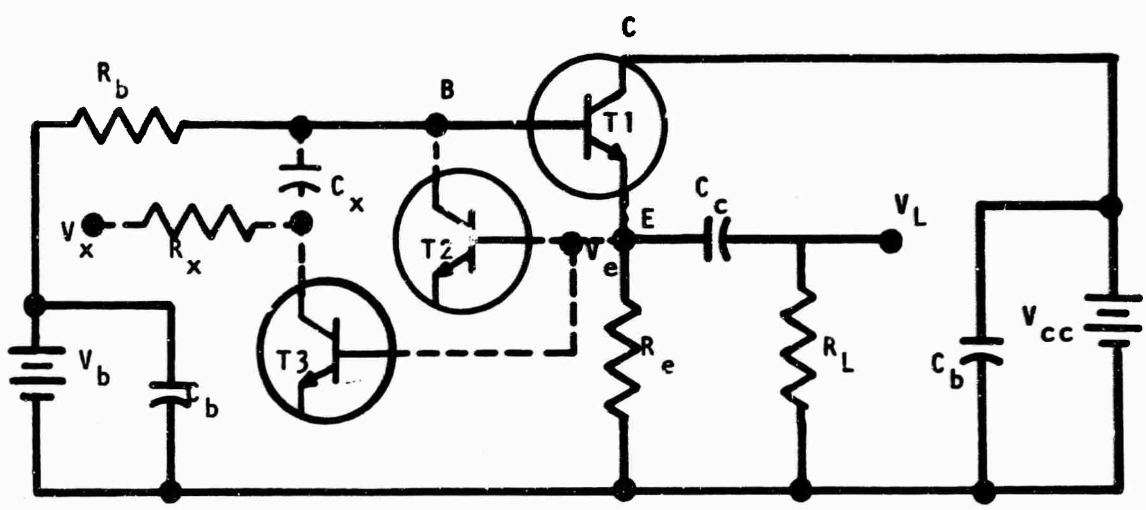


Figure 30. Circuit for Common-Collector Amplifier with Methods for Base-to-Emitter Compensation

possible to have $V_b = 0$ and still remain in cutoff. For cutoff operation, the peak of the output voltage is

$$\hat{V}_L = \hat{I}_c R_e \| R_L \tag{85}$$

The compensation junction increases the pulse output during irradiation.

Active Region. V is no longer zero, and secondary photocurrent generation occurs. The peak of the resulting voltage pulse is

$$\hat{V}_L = \frac{1}{D R_b r_b r_d} \left\{ -\left[\beta R_b - r_d - r_b\right] \hat{I}_c + (R_b + r_b)(1+\beta) \hat{I}_{pp} \right\} \tag{86}$$

where

$$D = \left(\frac{1}{R_b} + \frac{1}{r_b}\right)\left[\left(\frac{1}{r_b} + \frac{1}{r_d}\right)\left(\frac{1}{r_d} + \frac{1}{r} + g_m\right) - \frac{1}{r_d}\left(\frac{1}{r_d} + g_m\right)\right] - \frac{1}{r_b^2}\left(\frac{1}{r_d} + \frac{1}{r} + g_m\right) \tag{87}$$

and where $r = R_e \| R_L$. To achieve exact cancellation, make

$$\hat{I}_c = \frac{\left(1 + \frac{r_b}{R_b}\right)(1+\beta)}{\beta - \frac{r_d + r_b}{R_b}} \hat{I}_{pp} \tag{88}$$

From equation (88), note that usually $\hat{I}_c$ does not need to be very much larger than $\hat{I}_{pp}$; hence, identical junctions for T1 and the compensation junction may be used.

Saturation Region. For saturation-region operation, the current generator, $g_m V$, in the equivalent circuit is shorted out.

The resulting output voltage peak is given by

$$V_L = \left\{ - \frac{1}{r_b R_b} \hat{I}_{pp} + \frac{1}{R_b} \left(\frac{1}{r_b} + \frac{1}{r_d}\right) \hat{I}_c \right\} \frac{1}{D} \tag{89}$$

where

$$D = \left(\frac{1}{r_b} + \frac{1}{R_b}\right)\left[\left(\frac{1}{r_b} + \frac{1}{r_d}\right)\left(\frac{1}{r_d} + \frac{1}{r}\right) - \frac{1}{r_d^2}\right] - \frac{1}{r_b^2}\left(\frac{1}{r_d} + \frac{1}{r}\right) \tag{90}$$

and $r = r_c \| R_e \| R_L$

For best compensation,

$$\hat{I}_{pp} = \left(1 + \frac{r_b}{r_d}\right) \hat{I}_c \tag{91}$$

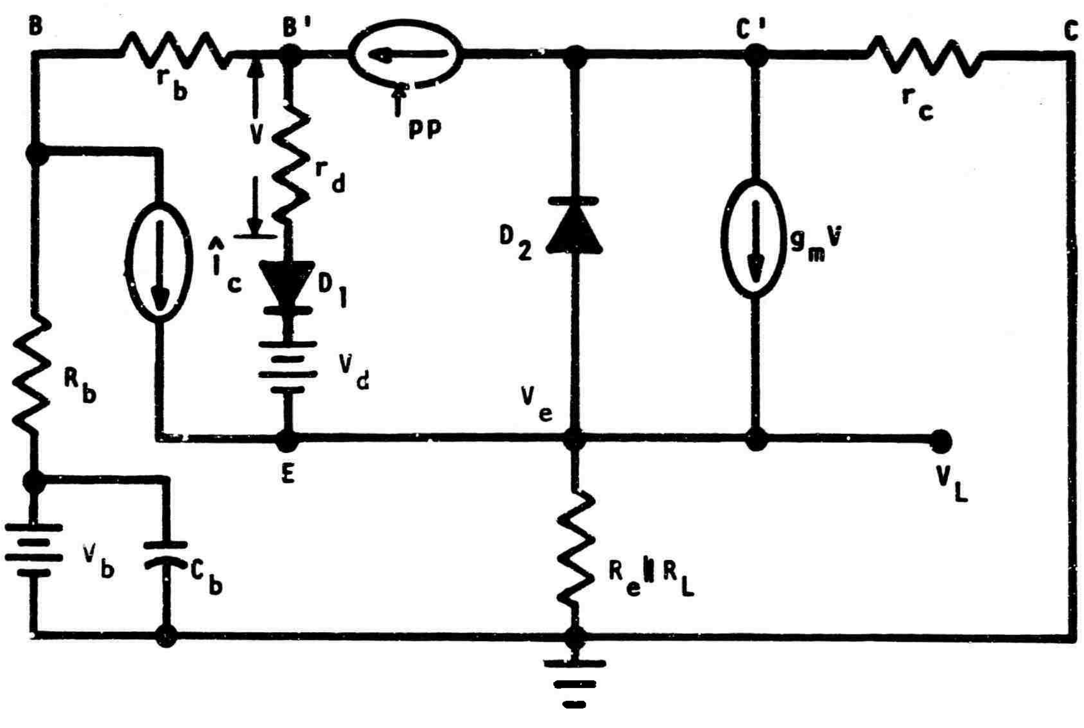


Figure 31. Equivalent Circuit for the Common-Collector Amplifier with Base-to-Emitter Compensation

7. <u>Common-Base Amplifier Stage Driving a Common-Collector Amplifier Stage</u>

Figure 32 shows a circuit diagram for a common-base amplifier stage driving a common-collector amplifier stage. This amplifier combination offers promise of having low inherent radiation response under certain conditions. The purpose of the analysis to follow is to provide crude estimates of the criteria required for low transient-radiation response. Capacitor coupling between the two stages is used so that the regions of operation of the two amplifiers may be selected by varying V_{eb} and V_b.

No junction compensation techniques are employed. Inherent compensation is present in this combination of amplifiers when the proper relationships exist between the primary photocurrents developed and other circuit parameters.

Figure 33 shows the ac- or pulse-equivalent circuit for this two-stage amplifier. All the parameters used have been defined in previous subsections. In some cases, an additional numerical subscript has been added to distinguish between the parameters for the two stages, as indicated in the figure.

All regions of operation (cutoff, active, and saturated) are investigated.

<u>Common-Base Amplifier Cut Off and Common-Collector Amplifier Cut Off</u>. The expression for the peak of the output voltage when both of the amplifier stages are cut off is

$$V_L = 0 \tag{92}$$

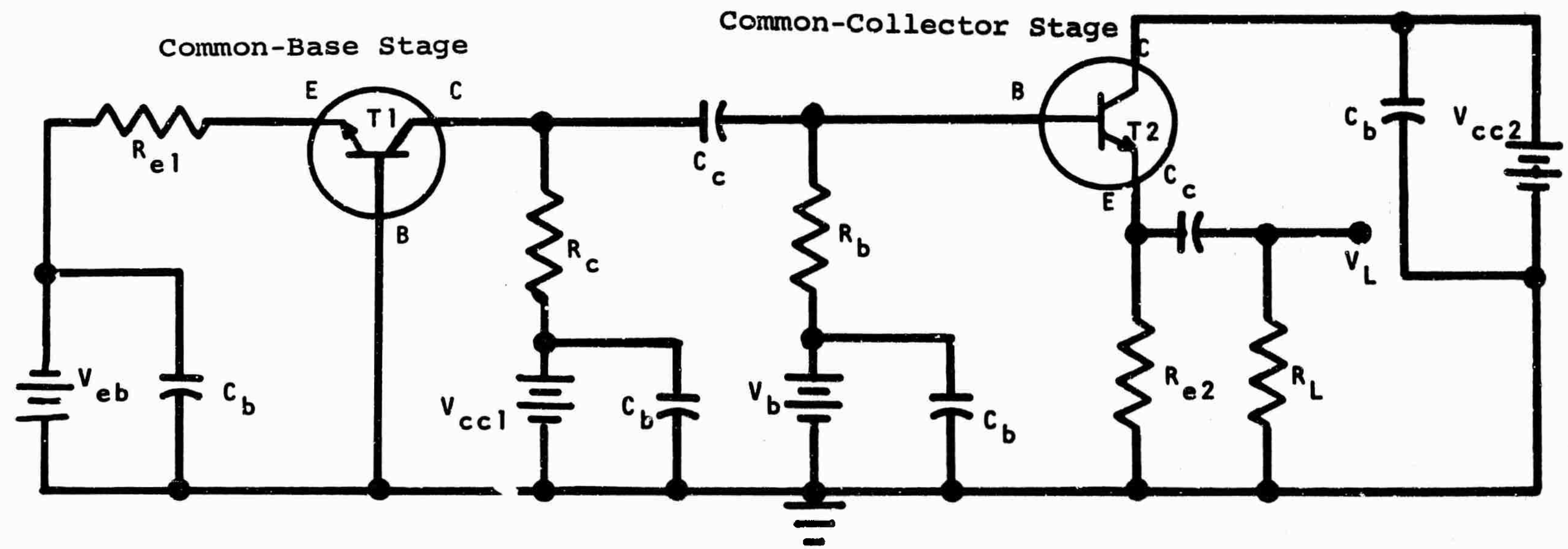


Figure 32. Circuit for a Common-Base Amplifier Driving a Common-Collector Amplifier

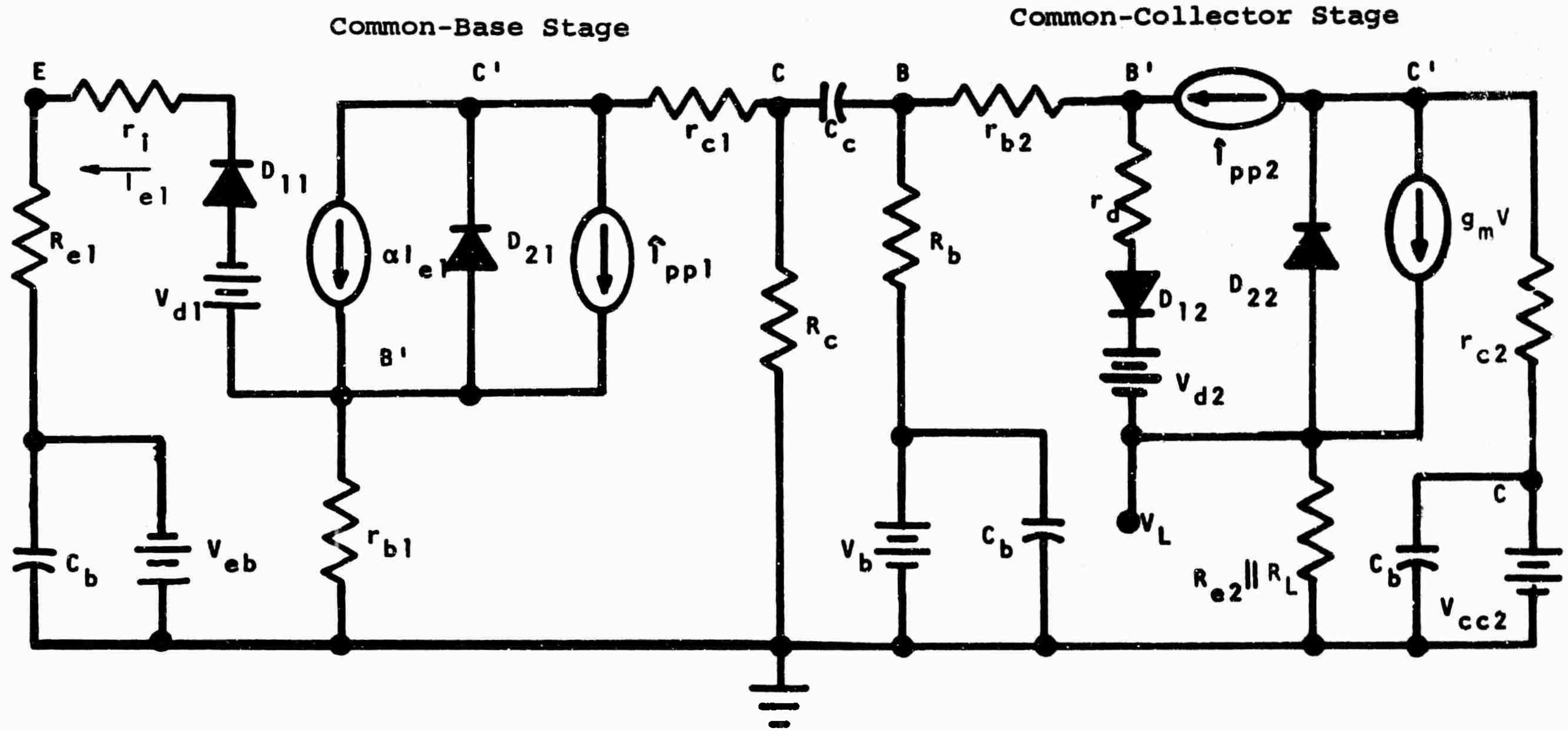


Figure 33. Equivalent Circuit for a Common-Base Amplifier Driving a Common-Collector Amplifier

Common-Base Amplifier Cut Off and Common-Collector Amplifier Active. The expression for the peak of the output voltage when the common-base stage is cut off and the common-collector stage is in the active region is

$$V_L = (1+\beta_2)\ R_{e2}\|R_L \left\{ \frac{(R_b\|R_c+r_{b2})\ \hat{I}_{pp2}}{R_b\|R_c+r_{b2}+r_d+(1+\beta_2)R_{e2}\|R_L} - \frac{R_c\|R_b\|\left[r_{b2}+r_d+(1+\beta_2)R_{e2}\|R_L\right]\ \hat{I}_{pp1}}{r_{b2}+r_d+(1+\beta_2)R_{e2}\|R_L} \right\} \tag{93}$$

In order to minimize the transient-radiation response, V_L, make

$$\hat{I}_{pp2} = \hat{I}_{pp1}\left[1 + \frac{R_b\|R_c}{r_{b2}+r_d+(1+\beta_2)R_{e2}\|R_L}\right] \cdot \frac{R_c\|R_b\|\left[r_{b2}+r_d+(1+\beta_2)R_{e2}\|R_L\right]}{R_b\|R_c+r_{b2}} \tag{94}$$

Common-Base Amplifier Cut Off and Common-Collector Amplifier Saturated. The next combination considered is for the common-base amplifier in cutoff and the common-collector amplifier in saturation. The peak of the output voltage is

$$V_L = \frac{-R_{e2}\|R_L\|r_{c2}\ I_{pp1}\ R_c\|R_b\|\left[r_{b2}+r_d+R_{e2}\|R_L\|r_{c2}\right]}{r_{b2}+r_d+R_{e2}\|R_L\|r_{c2}} + \frac{(R_b\|R_c+r_{b2})\ \hat{I}_{pp2}\ R_{e2}\|R_L\|r_{c2}}{R_b\|R_c+r_{b2}+r_d+R_{e2}\|R_L\|r_{c2}} \tag{95}$$

To minimize the transient-radiation-induced output voltage, make

$$\hat{I}_{pp2} = \hat{I}_{pp1} \left[1 + \frac{R_b \| R_c}{r_{b2}+r_d+R_{e2} \| R_L \| r_{c2}}\right] \cdot \frac{R_c \| R_b \| [r_{b2}+r_d+R_{e2} \| R_L \| r_{c2}]}{R_b \| R_c + r_{b2}} \qquad (96)$$

<u>Common-Base Amplifier Active and Common-Cclector Amplifier Cut Off</u>. For the common-base stage in the active region and the common-collector in cutoff, the response is

$$V_L \doteq 0 \qquad (97)$$

It is assumed that the radiation does not force the operation of the second stage out of the cutoff region.

<u>Common Base Amplifier Active and Common-Collector Amplifier Active</u>. One of the combinations of most interest is for both stages to be in the active region of operation. The resulting equation for the peak of the output pulse is

$$V_L = - \hat{I}_{pp1} \left[1 + \frac{\alpha_1 r_{b1}}{R_{e1}+r_i+(1-\alpha_1) r_{b1}}\right] R_c \| R_b \| \left[r_{b2}+r_d + (1+\beta_2) R_{e2} \| R_L\right] \frac{(1+\beta_2) R_{e2} \| R_L}{r_{b2}+r_d+(1+\beta_2) R_{e2} \| R_L} + \frac{(1+\beta_2)(R_b \| R_c + r_{b2}) \; \hat{I}_{pp2} \; R_{e2} \| R_L}{R_b \| R_c + r_{b2} + r_d + (1+\beta_2) \; R_{e2} \| R_L} \qquad (98)$$

The criteria for minimizing the response is

$$\hat{I}_{pp2} = \hat{I}_{pp1}\left[1 + \frac{R_b \| R_c}{r_{b2}+r_d+(1+\beta_2)R_{e2}\| R_L}\right]\left[1 + \frac{\alpha_1 r_{b1}}{R_{e1}+r_i+(1-\alpha_1)r_{b1}}\right] \cdot$$

$$\frac{R_c \| R_b \| [r_{b2}+r_d+(1+\beta_2)R_{e2}\| R_L]}{R_c \| R_b + r_{b2}} \tag{99}$$

<u>Common-Base Amplifier Active and Common-Collector Amplifier Saturated</u>. For the common-base stage in the active region and the common-collector saturated,

$$V_L = -\hat{I}_{pp1}\left[1 + \frac{\alpha_1 r_{b1}}{R_{ei}+r_i+(1-\alpha_1)r_{b1}}\right] R_c \| R_b \left[r_{b2}+r_d\right.$$

$$\left. + R_{e2}\| R_L \| r_{c2}\right] \frac{R_{e2}\| R_L \| r_{c2}}{r_{b2}+r_d+R_{e2}\| R_L \| r_{c2}}$$

$$+ \frac{(R_b \| R_c + r_{b2})\ \hat{I}_{pp2}\ R_{e2}\| R_L \| r_{c2}}{R_b \| R_c + r_{b2}+r_d+R_{e2}\| R_L \| r_{c2}} \tag{100}$$

To achieve the best compensation, the required relationship between $\hat{I}_{pp1}$ and $\hat{I}_{pp2}$ is

$$\hat{I}_{pp2} = \hat{I}_{pp1}\left[1 + \frac{R_b \| R_c}{r_{b2}+r_d+R_{e2}\| R_L \| r_{c2}}\right]\left[1 + \frac{\alpha_1 r_{b1}}{R_{e1}+r_i+(1-\alpha_1)r_{b1}}\right] \cdot$$

$$\frac{R_b \| R_c \| [r_{b2}+r_d+R_{e2}\| R_L \| r_{c2}]}{R_b \| R_c + r_{b2}} \tag{101}$$

<u>Common-Base Amplifier Saturated and Common-Collector Amplifier Cut Off</u>. For the common-base stage saturated and the common-collector stage cutoff, the output is

$$V_L \doteq 0 \tag{102}$$

Common-Base Amplifier Saturated and Common-Collector Amplifier Active. For this combination, the peak of the transient output pulse is

$$V_L = \frac{(1+\beta_2)\{R_b \| R_c \| [r_{c1}+r_{b1} \| (r_i+R_{e1})]+r_{b2}\} \hat{I}_{pp2} R_{e2} \| R_L}{R_b \| R_c \| [r_{c1}+r_{b1} \| (r_i+R_{e1})]+r_{b2}+r_d+(1+\beta_2) R_{e2} \| R_L} \tag{103}$$

Equation (103) involves no terms in $\hat{I}_{pp1}$, the first-stage primary photocurrent. Hence, no compensation can be made for this combination of circuit conditions.

Common-Base Amplifier Saturated and Common-Collector Amplifier Saturated. For this combination, the response is

$$V_L = \frac{\{R_b \| R_c \| [r_{c1}+r_{b1} \| (r_i+R_{e1})] + r_{b2}\} I_{pp2}\ R_{e2} \| R_L \| r_{c2}}{R_b \| R_c \| [r_{c1}+r_{b1} \| (r_i+R_{e1})] + r_{b2} + r_d+R_{e2} \| R_L \| r_{c2}} \tag{104}$$

Note, from equation (104), that no compensation is possible for this combination of circuit conditions.

8. Common-Emitter Amplifier Stage Driving a Common-Emitter Amplifier Stage

Another amplifier combination which offers promise of having low inherent transient-radiation response (with proper design) is shown in figure 34. It is the common-emitter amplifier stage driving another common-emitter amplifier stage. In the following analysis, crude estimates of the criteria required for low transient-radiation response are developed. Also, the combinations of regions of operation which are allowable are determined. Capacitor coupling is used between stages so that the region of operation for each amplifier stage is determined by varying V_{b1} and V_{b2}.

Junction compensation techniques are not employed for this amplifier. However, the proper relationship must be established between the primary photocurrents for T1 and T2 and certain other circuit parameters.

The ac- or pulse-equivalent circuit for this two-stage common-emitter amplifier is shown in figure 35. All combinations of regions of operation are analyzed. The parameters used in the equivalent circuit are defined in previous sections. An additional numeric subscript (1 or 2) is added to certain symbols to differentiate between the T1 or T2 amplifier-stage parameters respectively.

T1 Cut Off and T2 Cut Off. When both the amplifier stages are biased to cutoff, the peak of the output is

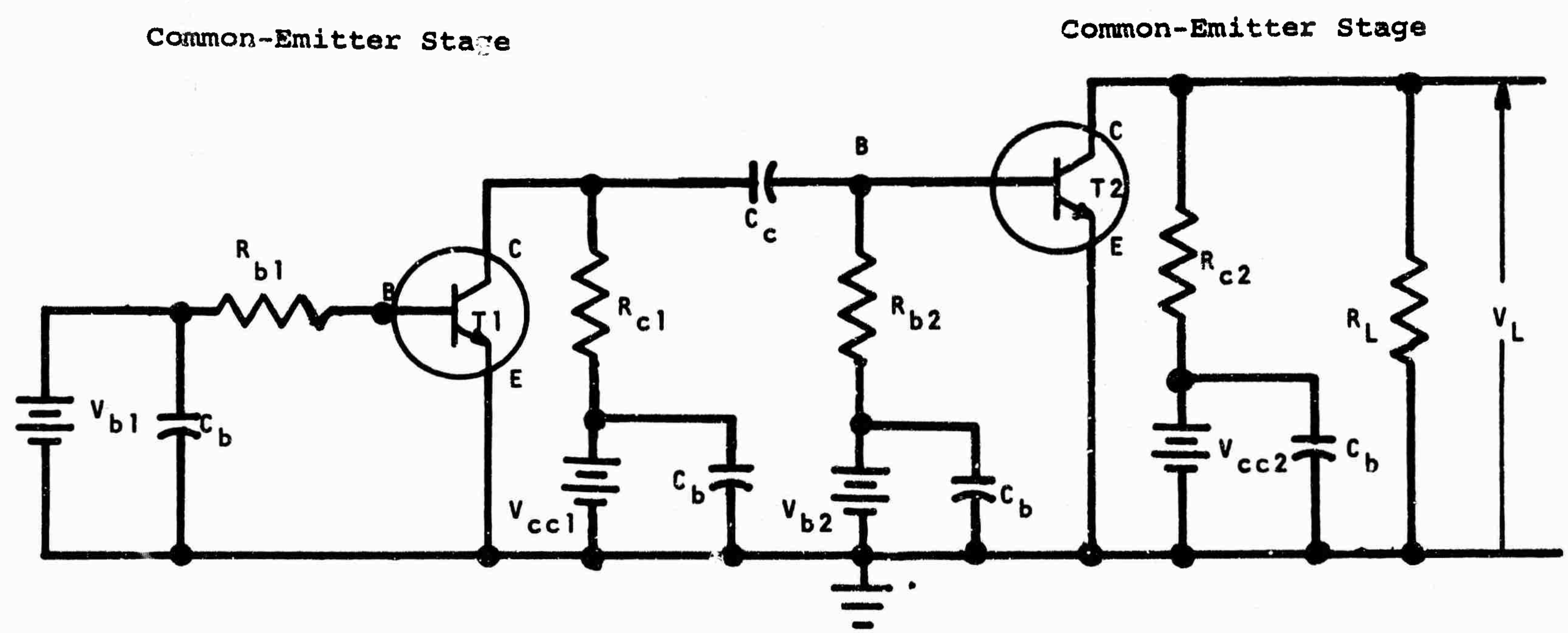


Figure 34. Circuit for a Common-Emitter Amplifier Driving a Common-Emitter Amplifier

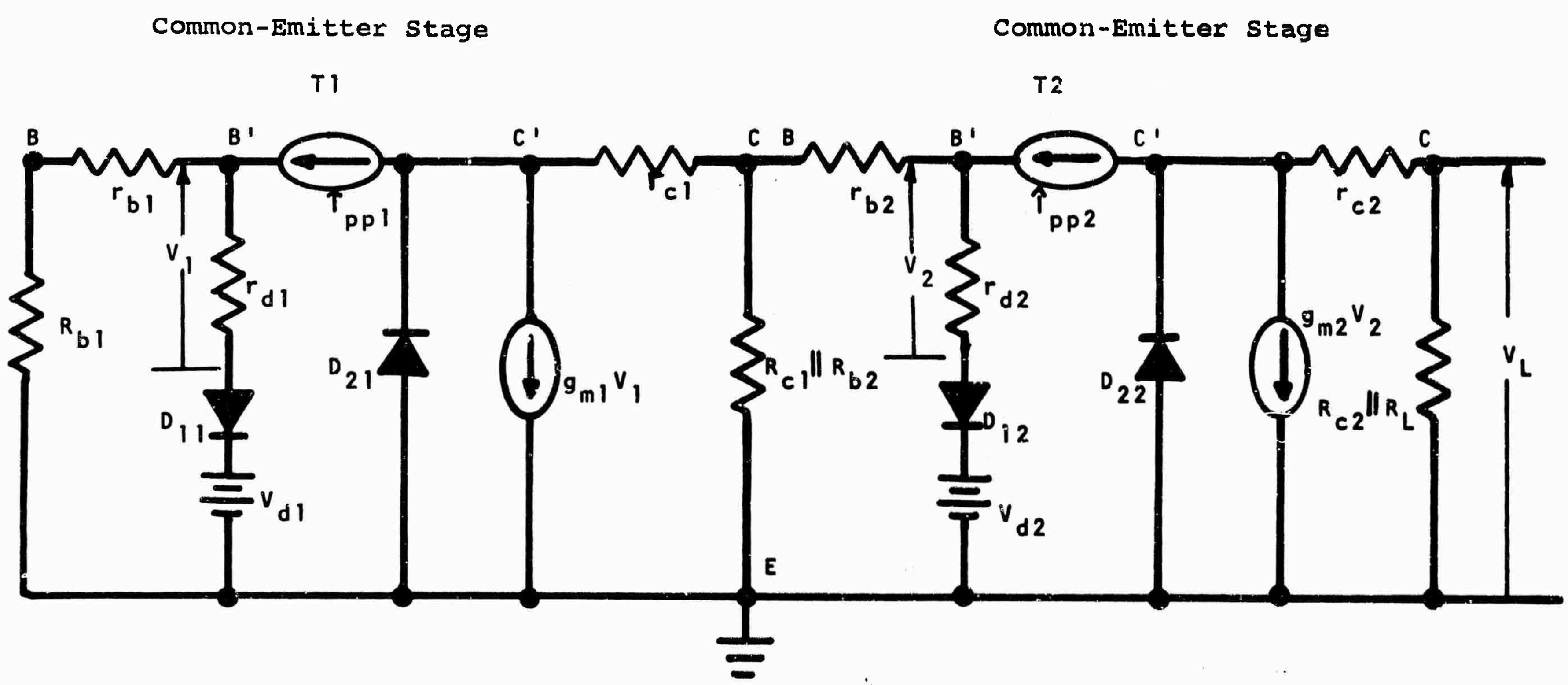


Figure 35. Equivalent Circuit for a Common-Emitter Amplifier Driving a Common-Emitter Amplifier

$$V_L = - \hat{I}_{pp2} R_{c2} \| R_L \quad (105)$$

and there is no way for compensation to be achieved. It is assumed that the radiation does not force either stage out of the cutoff region of operation.

<u>T1 Cut Off and T2 Active</u>. The output peak voltage is

$$V_L = + \hat{I}_{pp1} [R_{c1} \| R_{b2} \| (r_{b2}+r_{d2})] \frac{(\beta_2 R_{c2} \| R_L)}{r_{b2}+r_{d2}}$$

$$- \hat{I}_{pp2} R_{c2} \| R_L \left[1 + \frac{\beta_2 (R_{c1} \| R_{b2} + r_{b2})}{R_{c1} \| R_{b2} + r_{b2} + r_{d2}}\right] \quad (106)$$

To minimize the transient-output response, make

$$\hat{I}_{pp1} = \hat{I}_{pp2} \left[\frac{1}{\beta_2} + \frac{R_{c1} \| R_{b2} + r_{b2}}{R_{c1} \| R_{b2} + r_{b2} + r_{d2}}\right] \cdot \frac{(r_{b2}+r_{d2})}{R_{c1} \| R_{b2} \| (r_{b2}+r_{d2})}$$

$$(107)$$

Thus, $\hat{I}_{pp1}$ has to be made slightly larger than $\hat{I}_{pp2}$ for cancellation within these regions of operation.

<u>T1 Cut Off and T2 Saturated</u>. The output peak voltage is

$$V_L \doteq 0 \quad (108)$$

When the second stage is saturated, no transient output results.

<u>T1 Active and T2 Cut Off</u>. The output peak voltage is

$$V_L = - \hat{I}_{pp2} R_{c2} \| R_L \quad (109)$$

and there is no way for compensation to be achieved without the addition of a compensation junction.

T1 Active and T2 Active. For this combination, the peak of the output voltage is

$$V_L = +\hat{I}_{pp1}\left[1 + \frac{\beta_1(R_{b1}+r_{b1})}{R_{b1}+r_{b1}+r_{d1}}\right][R_{c1}\|R_{b2}\|(r_{b2}+r_{d2})] \cdot \left[\frac{\beta_2 R_{c2}\|R_L}{r_{b2}+r_{d2}}\right] - \hat{I}_{pp2}\, R_{c2}\|R_L\left[1 + \frac{\beta_2(R_{c1}\|R_{b2}+r_{b2})}{R_{c1}\|R_{b2}+r_{b2}+r_{d2}}\right] \tag{110}$$

To minimize the output response, make

$$\hat{I}_{pp1} = \hat{I}_{pp2}\left[\frac{1}{\beta_2} + \frac{R_{c1}\|R_{b2}+r_{b2}}{R_{c1}\|R_{b2}+r_{b2}+r_{d2}}\right] \cdot \frac{r_{b2}+r_{d2}}{R_{c1}\|R_{b2}\|(r_{b2}+r_{d2})} \cdot \frac{1}{1+\dfrac{\beta_1(R_{b1}+r_{b1})}{R_{b1}+r_{b1}+r_{d1}}} \tag{111}$$

A rough approximation of equation (111), is

$$\hat{I}_{pp2} = (1+\beta_1)\,\hat{I}_{pp1} \tag{112}$$

to achieve compensation. For both stages active, the T1 and T2 transistors would have to be different, with the two radiation primary photocurrents determined more accurately by equation (111).

T1 Active and T2 Saturated. The output peak voltage is

$$V_L \doteq 0 \tag{113}$$

<u>T1 Saturated and T2 Cut Off</u>. The output peak voltage is

$$V_L = -\hat{I}_{pp2}\, R_{c2} \| R_L \tag{114}$$

and no compensation is possible.

<u>T1 Saturated and T2 Active</u>. The output peak voltage is

$$V_L = -\hat{I}_{pp2}\, R_{c2} \| R_L \left[1 + \frac{\beta_2 (R_{c1} \| R_{b2} \| r_{c1} + r_{b2})}{R_{c1} \| R_{b2} \| r_{c1} + r_{b2} + r_{d2}} \right] \tag{115}$$

and no compensation is possible.

<u>T1 Saturated and T2 Saturated</u>. The output voltage peak is

$$V_L \doteq 0\ . \tag{116}$$

<u>Summary</u>. For T2 cut off, the output is

$$V_L = -\hat{I}_{pp2}\, R_{c2} \| R_L \tag{117}$$

and no compensation is possible.

For T2 saturated, the output is zero.

For T2 active and T1 cut off, make

$\hat{I}_{pp1}$ slightly larger than $\hat{I}_{pp2}$ for proper compensation.

For T2 active and T1 active, make

$\hat{I}_{pp2} = (1+\beta_1)\, \hat{I}_{pp1}$.

For T2 active and T1 saturated, no compensation is possible.

9. Common-Emitter Amplifier Stage Driving a Common-Collector Amplifier Stage

This combination, similar to the circuits considered in the previous two subsections, offers promise of having an inherent transient-radiation resistance when proper design techniques are applied. Most of the introductory comments made in the last two subsections apply here. All combinations of cutoff, active, and saturation regions of operation are considered. The circuit diagram is shown in figure 36, and its ac equivalent circuit is presented in figure 37.

T2 or Common-Collector Cut Off. Assume that by adjustment of the value of V_{b2} and/or the compensation effect of the first stage, the common-collector stage remains cut off during irradiation. Then the output voltage pulse is

$$V_L \doteq 0 \tag{118}$$

T1 Cut Off and T2 Active. For the common emitter in cutoff and the common collector in the active region, the peak of the output pulse is

$$V_L = -\hat{I}_{pp1}\, R_c \| R_{b2} \| [r_{b2} + r_{d2} + (1+\beta_2) R_e \| R_L] \cdot \frac{(1+\beta_2) R_e \| R_L}{r_{b2} + r_{d2} + (1+\beta_2) R_e \| R_L}$$

$$+ \frac{(1+\beta_2)(R_c \| R_{b2} + r_{b2})\, \hat{I}_{pp2}\, R_e \| R_L}{R_c \| R_{b2} + r_{b2} + r_{d2} + (1+\beta_2) R_e \| R_L} \tag{119}$$

To minimize the output response, make

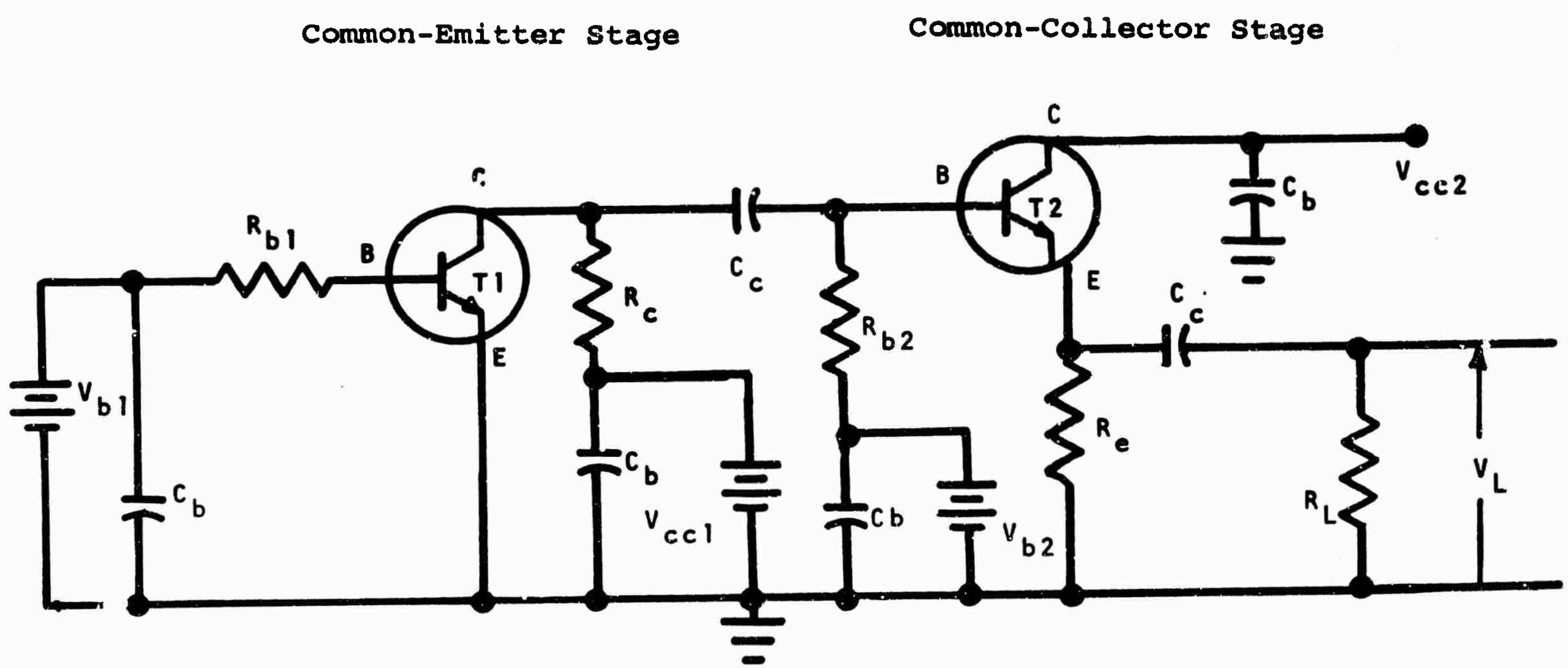


Figure 36. Circuit for Common-Emitter Amplifier Stage Driving a Common-Collector Amplifier Stage

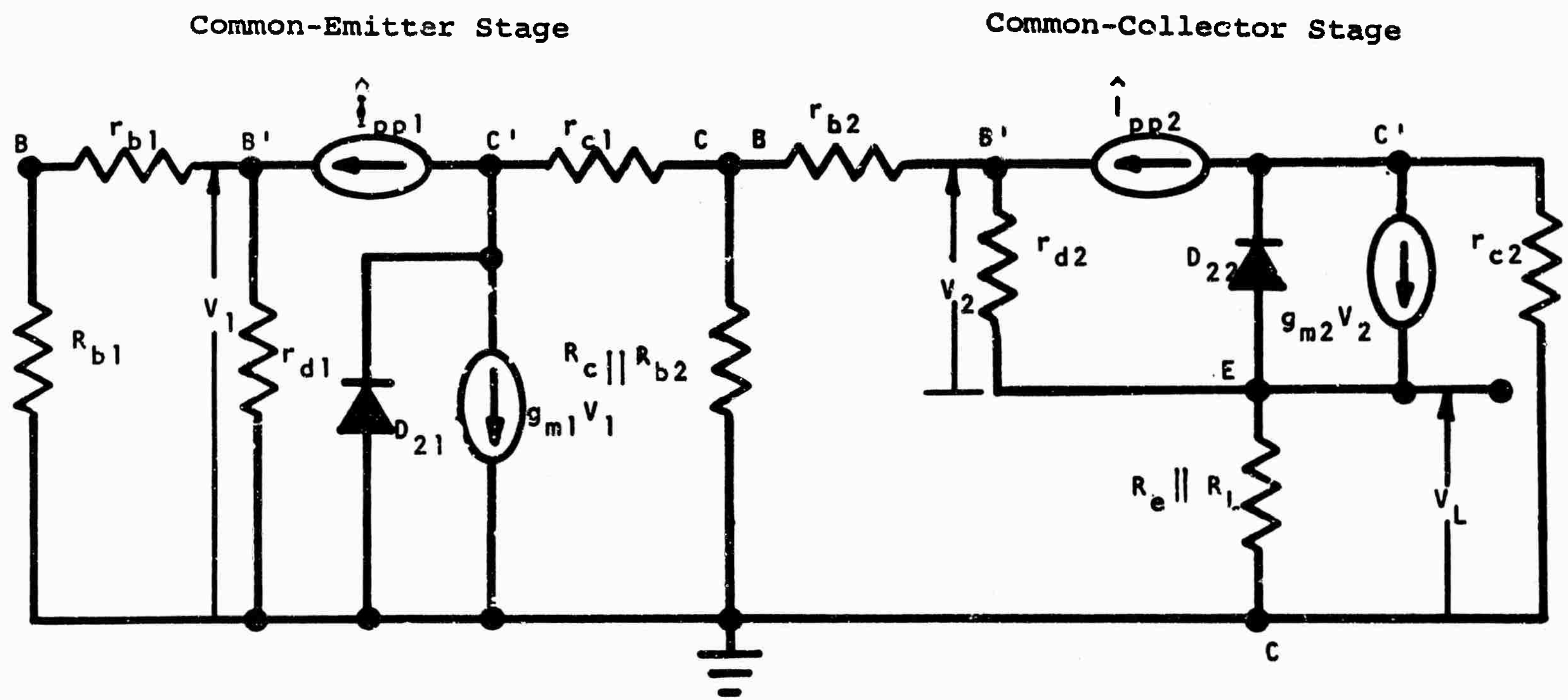


Figure 37. Equivalent Circuit for Common-Emitter Stage Driving a Common-Collector Stage

$$\hat{I}_{pp2} = \hat{I}_{pp1}\left[1 + \frac{R_c \| R_{b2}}{r_{b2} + r_{d2} + (1 + \beta_2) R_e \| R_L}\right] \cdot$$

$$\frac{R_c \| R_{b2} \| [r_{b2} + r_{d2} + (1 + \beta_2) R_e \| R_L]}{R_c \| R_{b2} + r_{b2}} \tag{120}$$

or approximately, make

$$\hat{I}_{pp2} \doteq \hat{I}_{pp1} \tag{121}$$

<u>T1 Cut Off and T2 Saturated</u>. For this combination, the peak of the output pulse is

$$V_L = -\hat{I}_{pp1} R_c \| R_{b2} \| [r_{b2} + r_{d2} + R_e \| R_L \| r_{c2}] \cdot$$

$$\frac{R_e \| R_L \| r_{c2}}{r_{b2} + r_{d2} + R_e \| R_L \| r_{c2}} +$$

$$\frac{(R_c \| R_{b2} + r_{b2})\ \hat{I}_{pp2}\ R_e \| R_L \| r_{c2}}{R_c \| R_{b2} + r_{b2} + r_{d2} + R_e \| R_L \| r_{c2}} \tag{122}$$

For minimum output response, make

$$\hat{I}_{pp2} = \hat{I}_{pp1}\left[1 + \frac{R_c \| R_{b2}}{r_{b2} + r_{d2} + R_e \| R_L \| r_{c2}}\right] \cdot$$

$$\frac{R_c \| R_{b2} \| [r_{b2} + r_{d2} + R_e \| R_L \| r_{c2}]}{R_c \| R_{b2} + r_{b2}} \tag{123}$$

or approximately, make

$$\hat{I}_{pp2} = \hat{I}_{pp1} \tag{124}$$

<u>T1 Active and T2 Active</u>. The peak of the output response is

$$V_L = -\hat{I}_{pp1}\left[1 + \frac{\beta_1(R_{b1} + r_{b1})}{R_{b1} + r_{b1} + r_{d1}}\right] \cdot$$

$$R_c \| R_{b2} \| [r_{b2} + r_{d2} + (1 + \beta_2)R_e \| R_L] \cdot$$

$$\frac{(1 + \beta_2)R_e \| R_L}{r_{b2} + r_{d2} + (1 + \beta_2)R_e \| R_L} +$$

$$\frac{(1 + \beta_2)(R_c \| R_{b2} + r_{b2})\ \hat{I}_{pp2}\ R_e \| R_L}{R_c \| R_{b2} + r_{b2} + r_{d2} + (1 + \beta_2)R_e \| R_L} \tag{125}$$

For minimum output response, make

$$\hat{I}_{pp2} = \hat{I}_{pp1}\left[1 + \frac{R_c \| R_{b2}}{r_{b2} + r_{d2} + (1 + \beta_2)R_e \| R_L}\right] \cdot$$

$$\frac{R_c \| R_{b2} \| [r_{b2} + r_{d2} + (1 + \beta_2)R_e \| R_L]}{R_c \| R_{b2} + r_{b2}} \cdot$$

$$\left[1 + \frac{\beta_1(R_{b1} + r_{b1})}{R_{b1} + r_{b1} + r_{d1}}\right] \tag{126}$$

or approximately, make

$$\hat{I}_{pp2} \doteq (1 + \beta_1)\hat{I}_{pp1} \tag{127}$$

<u>T1 Active and T2 Saturated</u>. The peak of the output pulse is

$$V_L = \hat{I}_{pp1}\left[1 + \frac{\beta_1(R_{b1} + r_{b1})}{R_{b1} + r_{b1} + r_{d1}}\right] \cdot$$

$$R_c \| R_{b2} \| [r_{b2} + r_{d2} + R_e \| R_L \| r_{c2}] \cdot$$

$$\frac{R_e \| R_L \| r_{c2}}{r_{b2} + r_{d2} + R_e \| R_L \| r_{c2}} +$$

$$\frac{(R_c \| R_{b2} + r_{b2})\hat{I}_{pp2} R_e \| R_L \| r_{c2}}{R_c \| R_{b2} + r_{b2} + r_{d2} + R_e \| R_L \| r_{c2}} \tag{128}$$

For minimum output response make

$$\hat{I}_{pp2} = \hat{I}_{pp1}\left[1 + \frac{R_c \| R_{b2}}{r_{b2} + r_{d2} + R_e \| R_L \| r_{c2}}\right] \cdot$$

$$\frac{R_c \| R_{b2} \| [r_{b2} + r_{d2} + R_e \| R_L \| r_{c2}]}{R_c \| R_{b2} + r_{b2}} \cdot$$

$$\left[1 + \frac{\beta_1(R_{b1} + r_{b1})}{R_{b1} + r_{b1} + r_{d1}}\right] \tag{129}$$

or approximately, make

$$\hat{I}_{pp2} \doteq (1 + \beta_1)\hat{I}_{pp1} \tag{130}$$

<u>T1 Saturated and T2 Active</u>. The peak of the output pulse is

$$V_L = \frac{(1 + \beta_2)(R_c \| R_{b2} \| r_{c1} + r_{b2})\hat{I}_{pp2} R_e \| R_L}{R_c \| R_{b2} \| r_{c1} + r_{b2} + r_{d2} + (1 + \beta_2) R_e \| R_L} \tag{131}$$

and no compensation is possible.

T1 Saturated and T2 Saturated. The peak of the output pulse is

$$V_L = \frac{(R_c \| R_{b2} \| r_{c1} + r_{b2}) \hat{I}_{pp2} R_e \| R_L \| r_{c2}}{R_c \| R_{b2} \| r_{c1} + r_{b2} + r_{d2} + R_e \| R_L \| r_{c2}} \tag{132}$$

and no compensation is possible.

Summary. For T2 cut off, the output is

$$V_L \doteq 0 \tag{133}$$

and no compensation is necessary.

For T1 cutoff and T2 active or saturated, make

$$\hat{I}_{pp2} \doteq \hat{I}_{pp1} \tag{134}$$

For T1 active and T2 active or saturated, make

$$\hat{I}_{pp2} \doteq (1 + \beta_1) \hat{I}_{pp1} \tag{135}$$

For T1 saturated and T2 active or saturated, no inherent compensation is possible.

SECTION IV

CIRCUS COMPUTER PROGRAM PREDICTIONS

1. CIRCUS Program

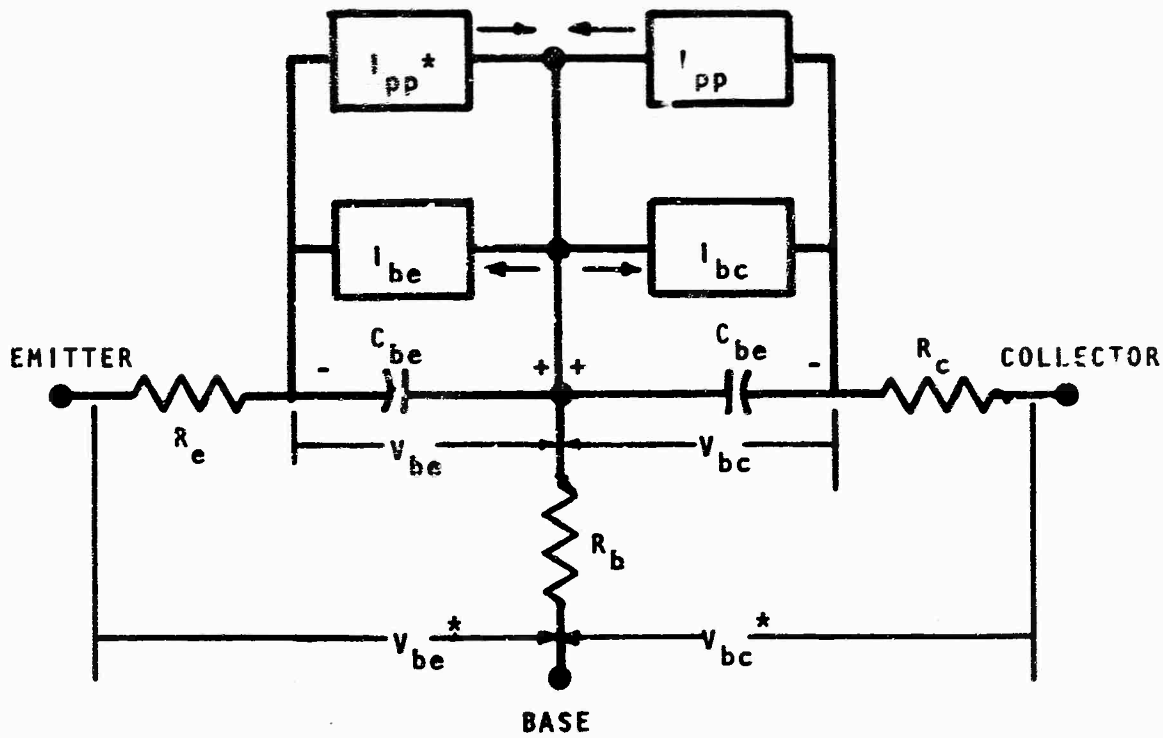
CIRCUS stands for CIRCUIT SIMULATOR. It is a digital computer program capable of performing the time-domain simulation of electrical circuits. This program was developed by The Boeing Aircraft Company for the purpose of simulating the effects of transient radiation upon systems and circuits. The program is written in FORTRAN and has been adapted for use on the CDC6600 computer at AFWL, Kirtland Air Force Base, where all the computer calculations were performed.

CIRCUS can analyze networks of general configuration containing resistors, inductors, capacitors, transistors, diodes, fixed and time-varying voltage sources, and time-varying current sources. The input required is a description of the circuit in terms of labels to identify the components, their terminal connections, and the value of the components. CIRCUS automatically solves the circuit dc-steady-state initial conditions and then uses these conditions to solve the differential equations for the transient solution. Reference 15 contains more detailed information about the use and application of CIRCUS.

Transistor Models. The charge-control transistor model is used. The model and the defining mathematical relationships are shown in figure 38. Note that the model

approximates the transient-radiation response by the inclusion of the primary photocurrent generators I_{pp} and I^*_{pp}. The parameters β_N, β_I, T_{CN}, and T_{CI} are tabled values as functions of the indicated variables. The correspondence between the model mathematical symbols and the program input data symbols are shown in Table I.

The biggest practical problem associated with the use of CIRCUS is the determination of the experimental values of the parameters used in the transistor models. Methods of experimentally determining these values are described in references 16, 17, and 18. All the analyzed circuits used the Texas Instruments 2N2368, for which the required parameters have already been determined by the Boeing Company (reference 18). However, verification checks were made on the value of the 2N2368 collector-to-base junction primary photocurrent during irradiation tests at the Kirtland Air Force Base flash X-ray facility. An additional purpose of this test was to determine the dependence of the resulting primary photocurrent on the collector-to-base junction voltage. This dependence results from the variation of the depletion component of the photocurrent with voltage. It was found that the resulting current varied markedly with voltage. This information was used to vary the value of photocurrent for certain computations.



$$I_{be} = \left(\frac{1}{\beta_N} + 1\right) I_N - I_I$$

$$I_{bc} = -I_N + \left(\frac{1}{\beta_I} + 1\right) I_I$$

$$I_N = I_{es}\left(e^{\theta_N V_{be}} - 1\right)$$

$$I_I = I_{cs}\left(e^{\theta_I V_{bc}} - 1\right)$$

$$C_{be} = \frac{a_1}{(\phi_1 - V_{be})^{n_1}} + \theta_N T_{CN}(I_N + I_{es})$$

$$C_{bc} = \frac{a_2}{(\phi_2 - V_{bc})^{n_2}} + \theta_I T_{CI}(I_I + I_{cs})$$

TABLED VALUES

$\beta_N = f(I_N)$, $\beta_I = f(I_I)$

$T_{CN} = f(I_N)$, $T_{CI} = f(I_I)$

Figure 38. CIRCUS Charge-Control Model for n-p-n Transistor, Including Transient-Radiation Effects

TABLE I

CIRCUS Transistor Symbol Correspondence

Mathematical Symbol (Fig. 8)	Data Symbol
Single-valued Parameters	
R_b	RB
R_c	RC
R_e	RE
a_1	A1
n_1	N1
φ_1	PHI1
a_2	A2
n_2	N2
φ_2	PHI2
θ_N	THETAN
θ_i	THETAI
i_{es}	IES
i_{cs}	ICS
Tabled Parameters	
β_N	BN
β_I	BI
T_{CN}	TCN
T_{CI}	TCI

Gamma-Ray Pulse Shape. All the circuits which were analyzed by CIRCUS (as explained in this section) were also experimentally tested on the Field Emission Corporation 2-Mev flash X-ray machine at AFWL,Kirtland Air Force Base. Most of these tests were made at approximately the 10^9 to 10^{10} R/sec level. So that predicted and experimental results could be compared, computer calculations were made at both the 10^9 and the 10^{10} R/sec X-ray levels. A form which closely simulates the form of the flash X-ray radiation output was assumed for the radiation-pulse shape. This pulse shape is shown in figure 39. In the CIRCUS program, a value for the transistor primary photocurrent is specified for a particular radiation rate. The program automatically makes a linear extrapolation of this value to the new value associated with the instantaneous level of radiation.

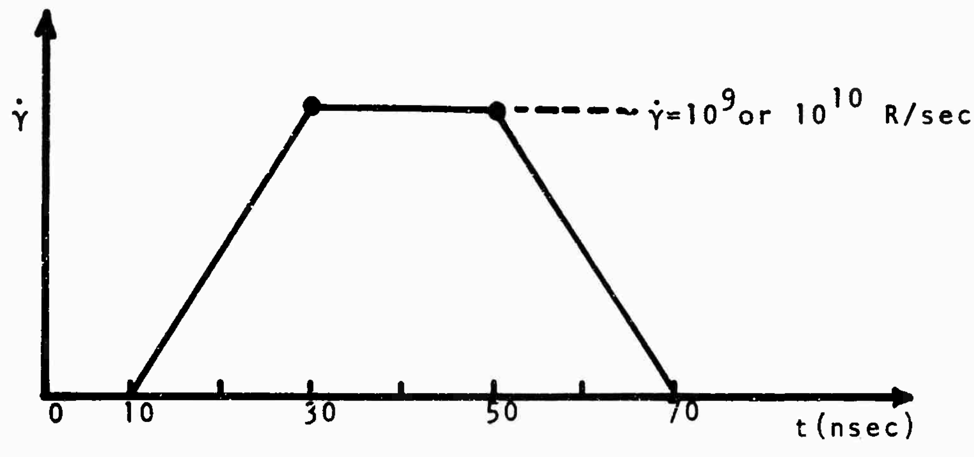


Figure 39. Gamma Ray Pulse Shape for CIRCUS

The $\hat{I}_{pp}$ value rated for the 2N2368 with a collector-to-base voltage of about 20 volts is 80μa at $\dot{\gamma} = 10^8$ R/sec. Thus, within the program, the peak values of I_{pp} were 800μa and 8000μa, respectively, for $\dot{\gamma} = 10^9$ and 10^{10} R/sec.

<u>Purpose of the Computations</u>. The main purposes of these computer calculations were to allow a fairly direct comparison of the approximate theoretical results and the experimental results with those predicted by computer techniques.

2. <u>Computer Results for a Common-Emitter Amplifier with no Compensation</u>

A basic common-emitter amplifier with no compensation present is shown in figure 40. The component symbols and node numbers correspond to those used in the computer program description. Part of the junction-compensation source voltage circuit is included but the compensation junction is replaced by two high-value resistors, RJ and RK.

The CIRCUS input for the run V2 = 0 is shown in Table II. By referring to figure 40 and Table II, the method of describing a circuit to CIRCUS is fairly obvious.

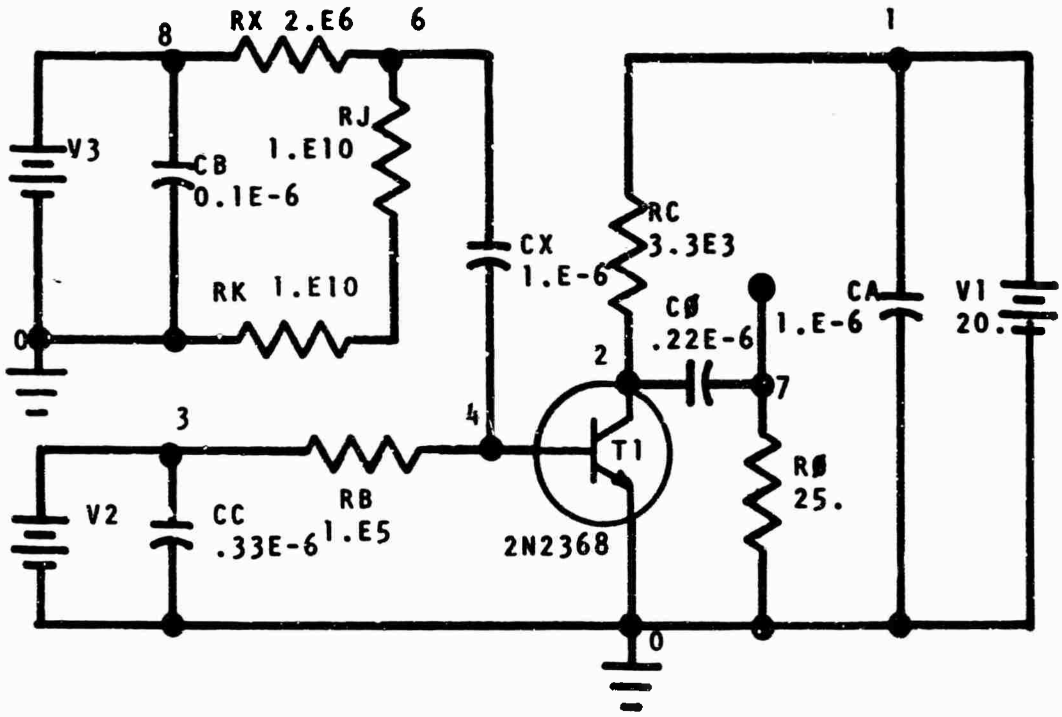
As V2 is increased, the collector-to-base voltage of T1 decreases. To account for the decrease of the depletion component of photocurrent with decreasing junction voltage, I_{pp} was decreased for increasing V2. Based on experimental

data, the required variations, associated with a radiation reference level of $\gamma = 10^8$ R/sec, were as follows.

$$V2 = 0.0, \qquad I_{pp} = 78.0 \times 10^{-6} \text{amp}$$
$$V2 = 3.0, \qquad I_{pp} = 71.5 \times 10^{-6} \text{amp}$$
$$V2 = 6.5, \qquad I_{pp} = 61.5 \times 10^{-6} \text{amp}$$
$$V2 = 13.0, \qquad I_{pp} = 42.0 \times 10^{-6} \text{amp}$$
$$V2 = 18.3, \qquad I_{pp} = 27.0 \times 10^{-6} \text{amp}$$
$$V2 = 23.7, \qquad I_{pp} = 25.7 \times 10^{-6} \text{amp}$$

The values of V2 correspond to those used for the experimental transient-radiation testing of the circuit.

The plots of the resulting computer predictions of the output pulse (VN7) in volts are shown in figures 41 and 42 for $\dot{\gamma} = 10^9$ and 10^{10} R/sec, respectively. The graphs are for VN7 as a function of time (t in nanoseconds) with parameter variations of V2. Note that the output response decreases (as expected) as saturation is approached.



Values in volts, ohms, and farads

Figure 40. Common-Emitter Amplifier with no Compensation

TABLE II

CIRCUS Input for a Common-Emitter Amplifier with no Compensation

```
DEVICE PAPAMETERS
TRANSISTOR,2N2368,NPN,RB,30.,RC,20.,RE,.01,A1,5.25E-12,
PHI1,1.,N1,.31,
A2,3.18E-12,PHI2,.9,N2,.1,IES,1.29E-15,ICS,1.45E-13,
THETAN,40.2,THETAI,29.7
BN,.01,40.
BI,.01,.1
TCN,.01,4.1E-10
TCI,.01,9.E-8
END
  COMMON EMITTER-NO COMPENSATION  V2 = 0.
T1,4,2,0,2N2368
V1,0,1,20.
V2,0,3,0.
V3,0,8,40.
RB,3,4,1.E5
RC,1,2,3.3E3
RO,7,0,25.
RJ,6,5,1.E10
RK,5,0,1.E10
RX,6,8,2.E6
CA,0,1,1.E-6
CO,2,7,.22E-6
CX,4,6,1.E-6
CB,8,0,.1E-6
CC,3,0,.33E-6
PHOTOCURRENT,2N2368,IPP,1.E8,0.,70.E-9,
0.,10.E-9,30.E-9,50.E-9,70.E-9,
0.,0.,78.E-6,78.E-6,0.
PEAK RATE,1.E9,1.E10
PRINT,VN2,VN4,VN7
INTERVALS,10.E-9,490.E-9
EXECUTE
```

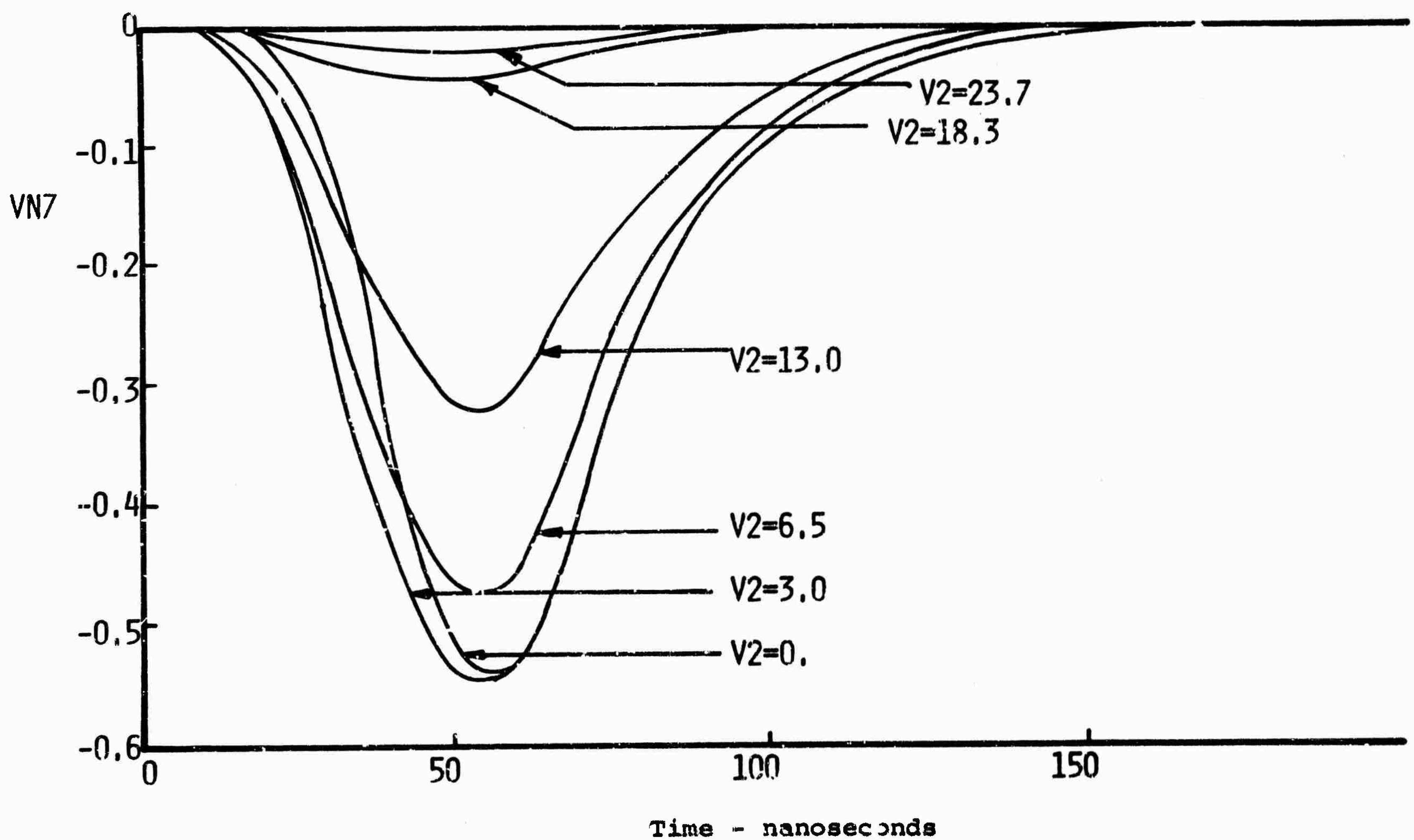


Figure 41. Common-Emitter Amplifier with no Compensation, $\dot{\gamma} = 10^9$ R/sec

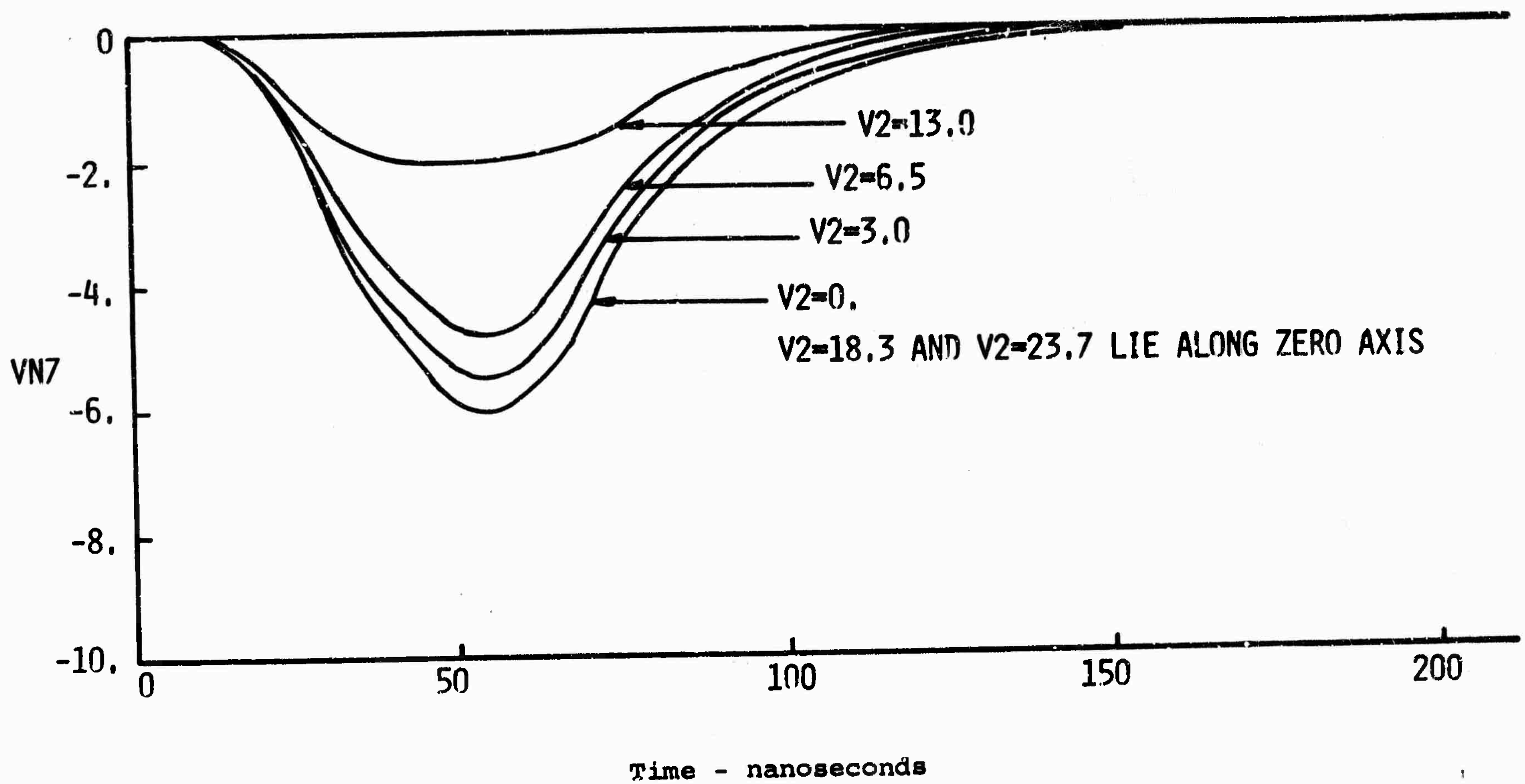


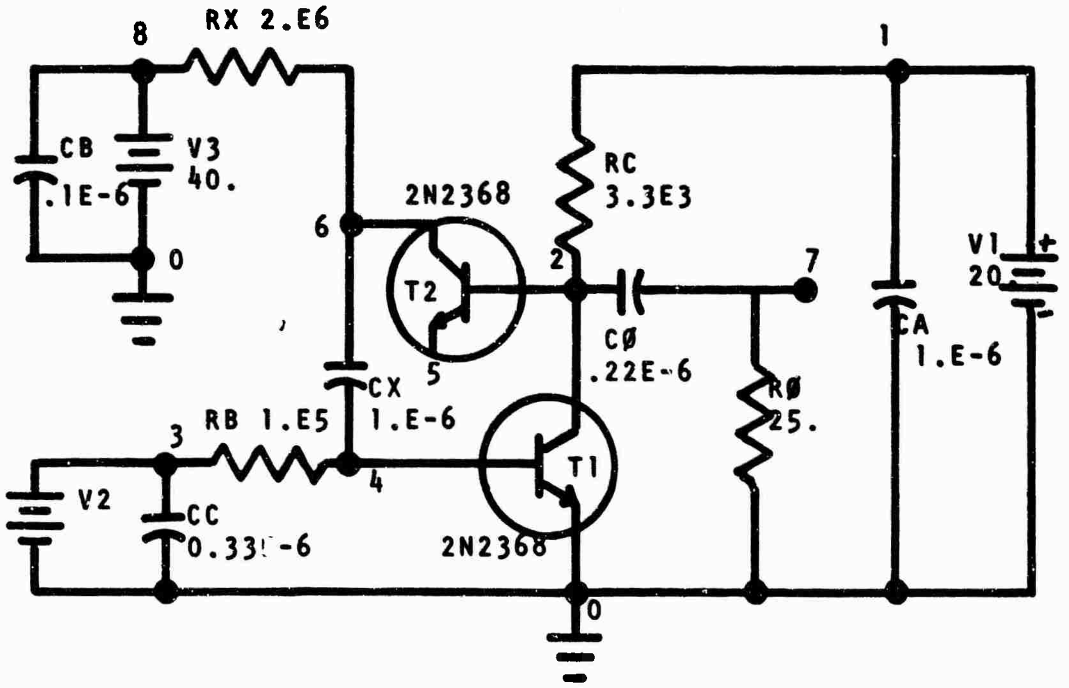
Figure 42. Common-Emitter Amplifier with no Compensation, $\dot{\gamma} = 10^{10}$ R/sec

3. Computer Results for a Common-Emitter Amplifier with Collector-to-Base Compensation

The basic common-emitter amplifier analyzed in section IV-2 is now analyzed with a compensation junction added from the collector-to-base compensation of T1. The compensation junction is assigned the same value of I_{pp} as T1. The values of I_{pp} for V2 as previously discussed are used.

The CIRCUS input is given in Table III. Figure 43 shows the circuit diagram.

The plots of the computed output responses are shown in figures 44 and 45. Note that the compensation has reduced the amplitude of the output as compared to that with no compensation(see figures 41 and 42).



Values in volts, ohms, and farads

Figure 43. Common-Emitter Amplifier with Collector-to-Base Cancellation

TABLE III

CIRCUS Input for a Common-Emitter Amplifier with Collector-to-Base Compensation

```
DEVICE PARAMETERS
TRANSISTOR,2N2368,NPN,RB,30.,RC,20.,RE,.01,A1,5.25E-12,
PHI1,1.,N1,.31,
A2,3.18E-12,PHI2,.9,N2,.1,IES,1.29E-15,ICS,1.45E-13,
THETAN,40.2,THETAI,29.7
BN,.01,40.
BI,.01,.1
TCN,.01,4.1E-10
TCI,.01,9.E-8
END
   COMMON EMITTER COLLECTOR-TO-BASE CANCELLATION  V2 = 0.
T1,4,2,0,2N2368
T2,2,6,5,2N2368
V1,0,1,20.
V2,0,3,0.
V3,0,8,40.
RB,3,4,1.E5
RX,6,8,2.E6
RC,1,2,3.3E3
RO,7,0,25.
CA,0,1,1.E-6
CO,2,7,0.22E-6
CC,0,3,0.33E-6
CX,4,6,1.E-6
CB,8,0,.1E-6
PHOTOCURRENT,2N2368,IPP,1.E8,0.,70.E-9,
0.,10.E-9,30.E-9,50.E-9,70.E-9,
0.,0.,78.E-6,78.E-6,0.
PEAK RATE,1.E9,1.E10
PRINT,VN2,VN4,VN7
INTERVALS,10.E-9,490.E-9
EXECUTE
```

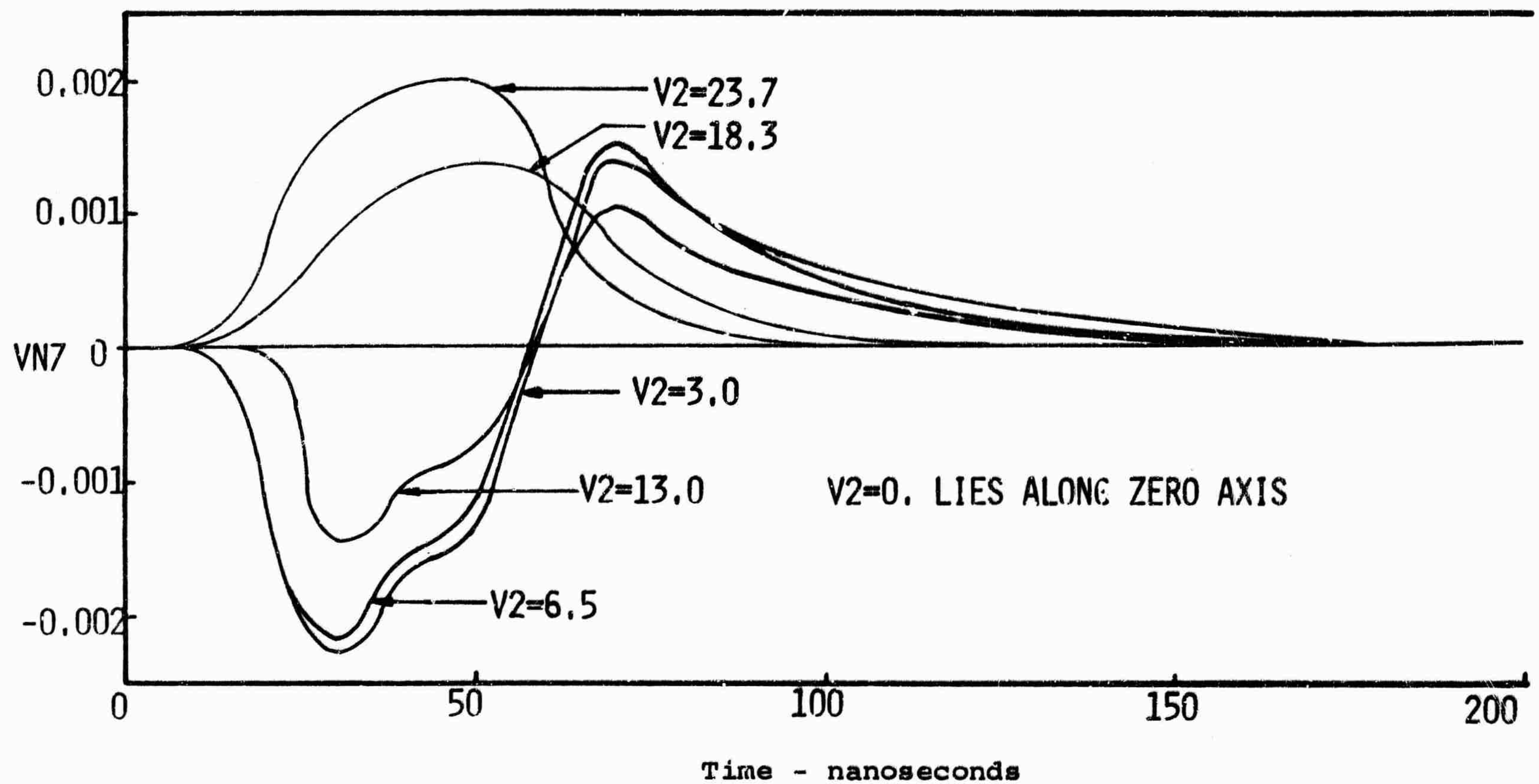


Figure 44. Common-Emitter Amplifier with Collector-to-Base Compensation, $\dot{\gamma} = 10^9$ R/sec

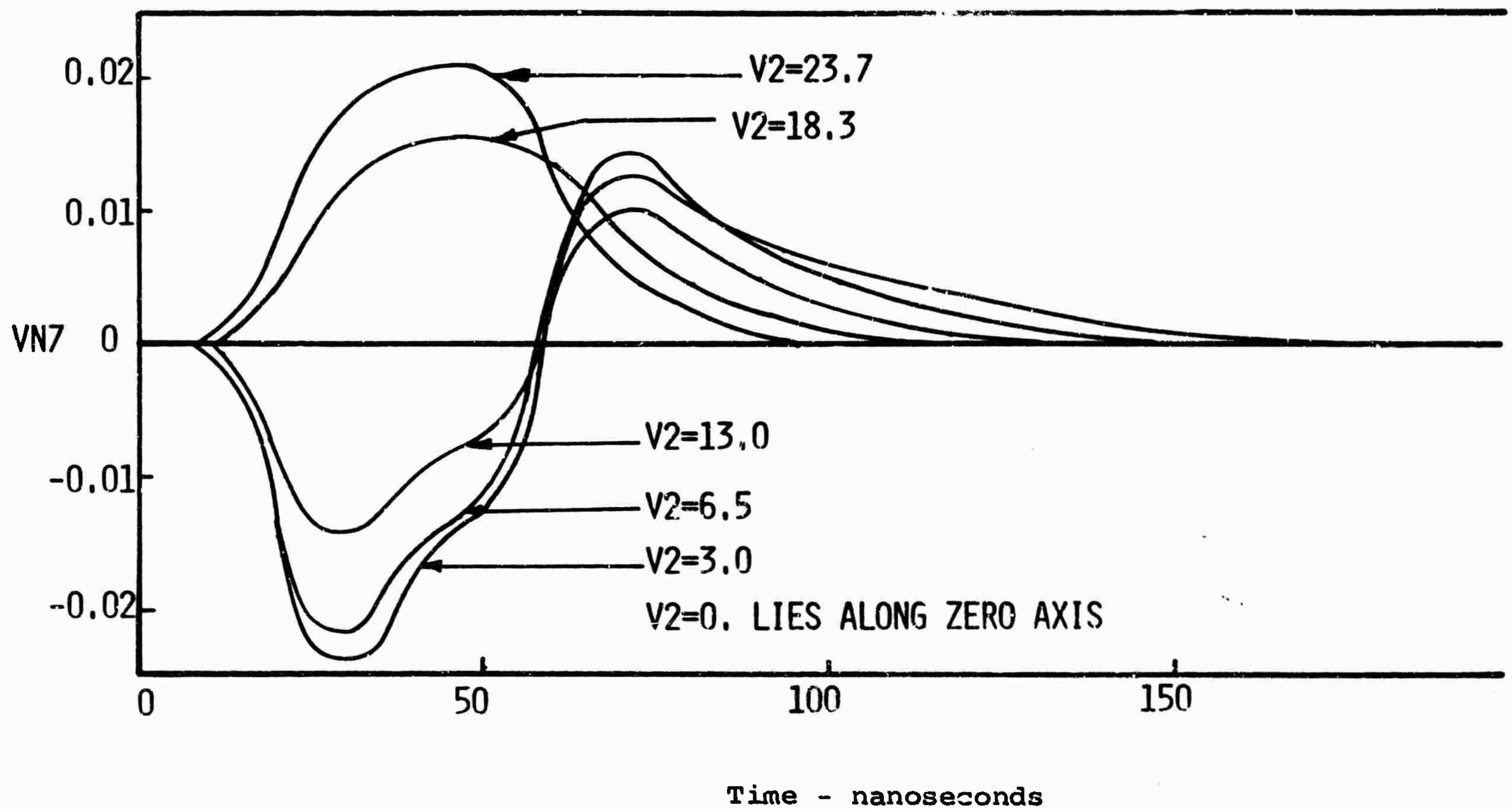


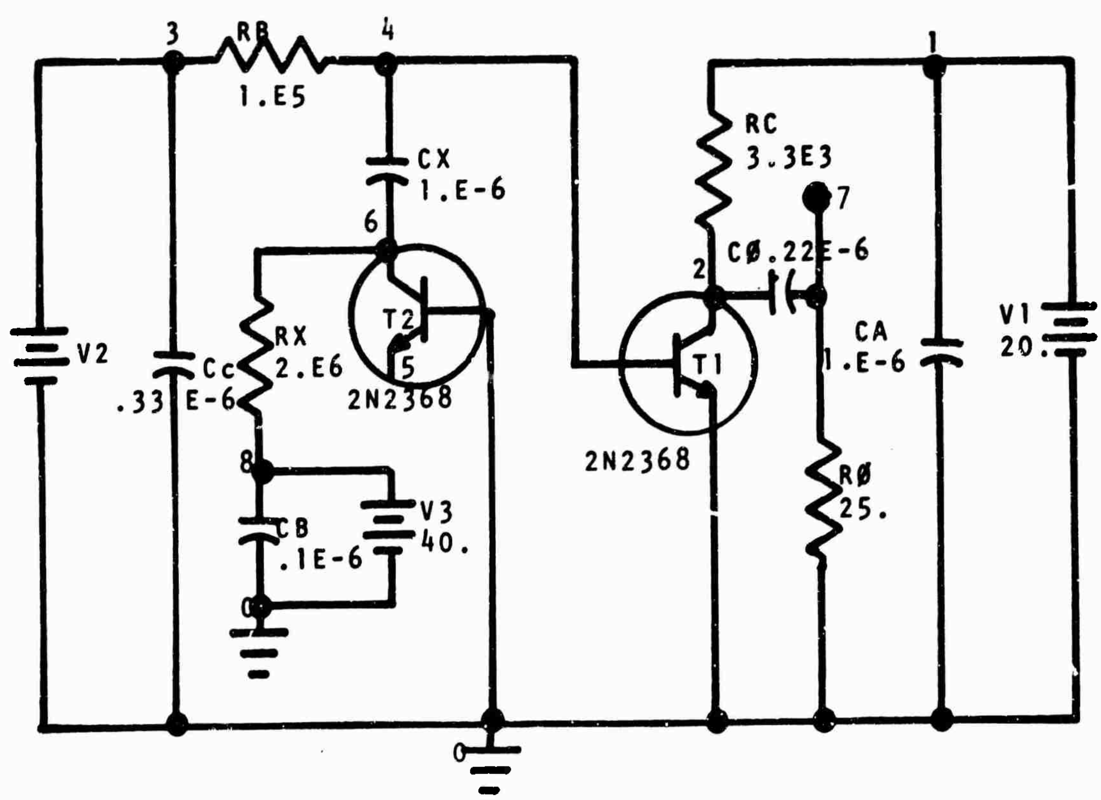
Figure 45. Common-Emitter Amplifier with Collector-to-Base Compensation, $\dot{\gamma} = 10^{10}$ R/sec

4. Computer Results for a Common-Emitter Amplifier with Base-to-Ground Compensation

The basic common-emitter amplifier is now analyzed with a compensation junction added from the base of T1 to ground. As previously, I_{pp} is varied with changes of V2.

In figure 46 the circuit diagram is shown. The CIRCUS input is given in Table IV.

The plots of the computed output pulses are shown in figures 47 and 48. The compensation has reduced the output magnitude, as compared with that shown in figures 41 and 42, The compensation photocurrent should be made slightly larger than the active device photocurrent if further reduction is desired (see equations 27 and 28).



Values in volts, ohms, and farads

Figure 46. Common-Emitter Amplifier with Base-to-Ground Cancellation

TABLE IV

CIRCUS Input for a Common-Emitter Amplifier
with Base-to-Ground Compensation

```
DEVICE PARAMETERS
TRANSISTOR,2N2368,NPN,RB,30.,RC,20.,RE,.01,A1,5.25E-12,
PHI1,1.,N1,.31,
A2,3.18E-12,PHI2,.9,N2,.1,IES,1.29E-15,ICS,1.45E-13,
THETAN,40.2,THETAI,29.7
BN,.01,40.
BI,.01,.1
TCN,.01,4.1E-10
TCI,.01,9.E-8
END
   COMMON EMITTER BASE-TO-GROUND CANCELLATION  V2 = 0.
T1,4,2,0,2N2368
T2,0,6,5,2N2368
V1,0,1,20.
V2,0,3,0.
V3,0,8,40.
RB,3,4,1.E5
RX,6,8,2.E6
RC,1,2,3.3E3
RO,7,0,25.
CA,0,1,1.E-6
CO,2,7,0.22E-6
CC,0,3,0.33E-6
CX,4,6,1.E-6
CB,8,0,.1E-6
PHOTOCURRENT,2N2368,IPP,1.E8,0.,70.E-9,
0.,10.E-9,30.E-9,50.E-9,70.E-9,
0.,0.,78.E-6,78.E-6,0.
PEAK RATE,1.E9,1.E10
PRINT,VN2,VN4,VN7
INTERVALS,10.E-9,490.E-9
EXECUTE
```

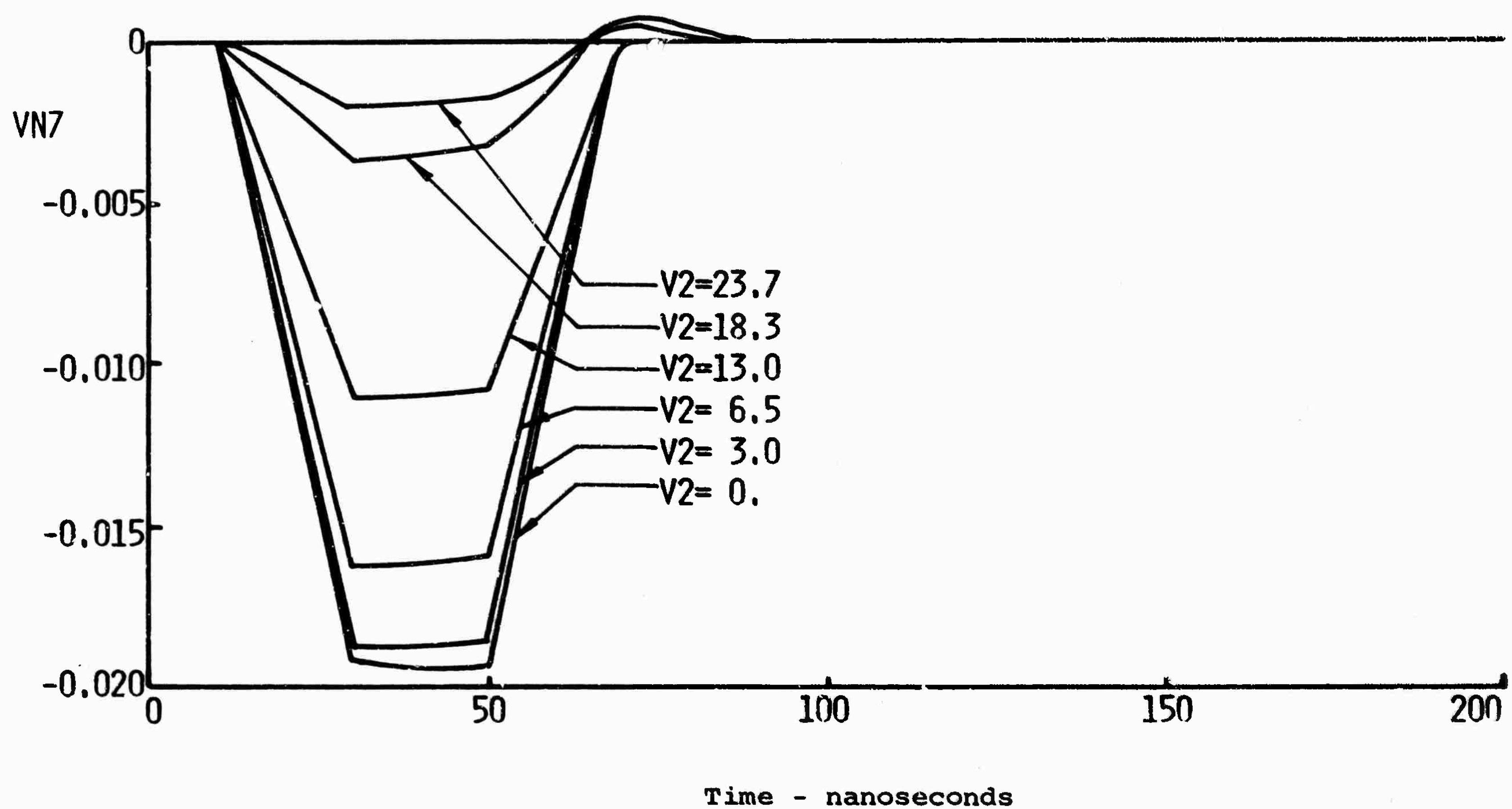


Figure 47. Common-Emitter Amplifier with Base-to-Ground Compensation, $\dot{\gamma} = 10^9$ R/sec

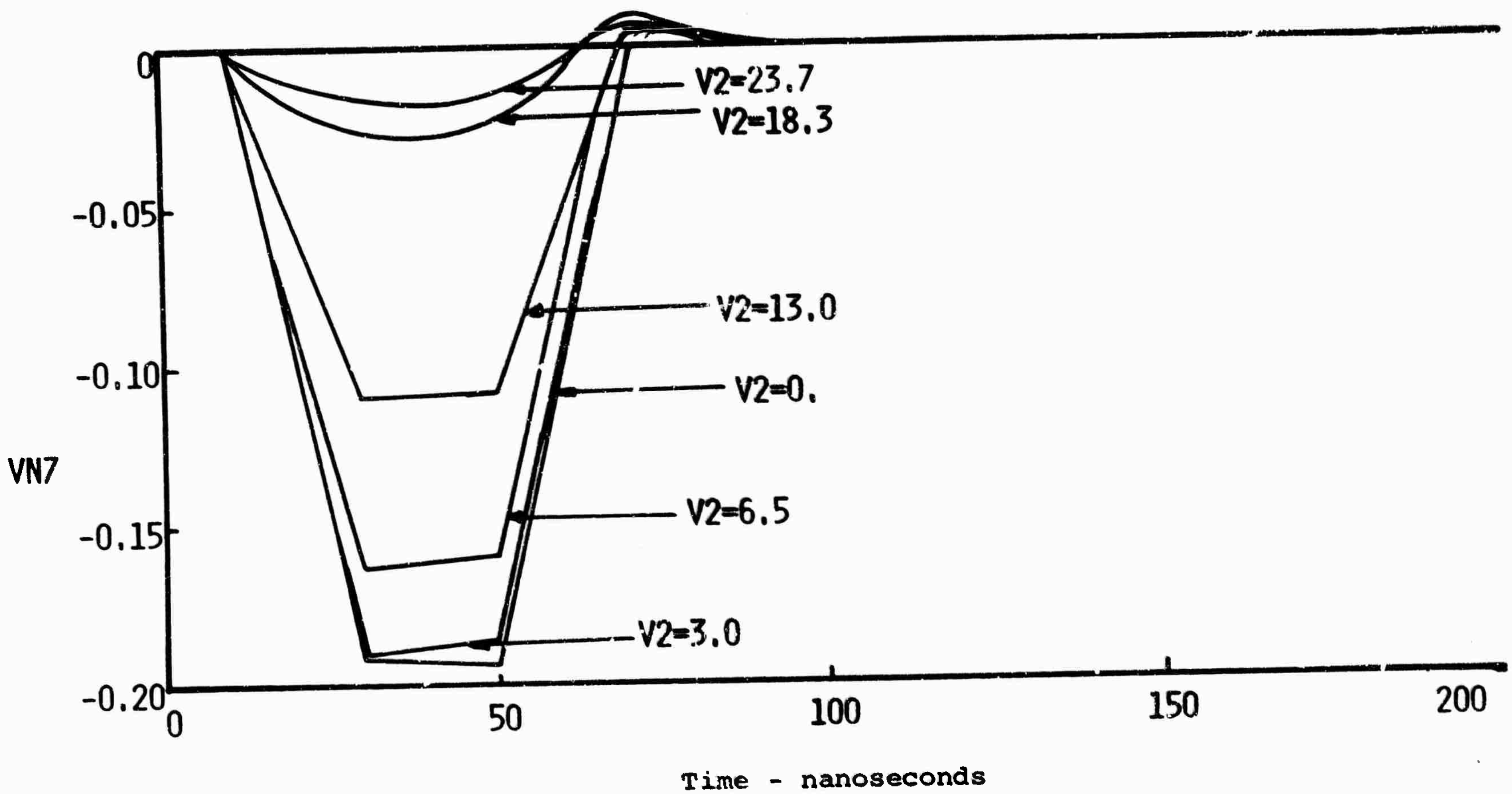


Figure 48. Common-Emitter Amplifier with Base-to-Ground Compensation $\dot{\gamma} = 10^{10}$ R/sec

5. Computer Results for a Common-Base Amplifier with no Compensation

The CIRCUS computer program analysis of the basic common-base amplifier with no compensation is now given. The collector-to-base voltage of the common-base amplifier also decreases with increasing base-to-emitter forward bias. Thus, based on experimental data, the required variations, associated with a radiation reference level of $\dot{\gamma} = 10^8$ R/sec, were as follows,

$V_e = 0.0,$ $I_{pp} = 65.0 \times 10^{-6}$ amp

$V_e = 10.5,$ $I_{pp} = 63.0 \times 10^{-6}$

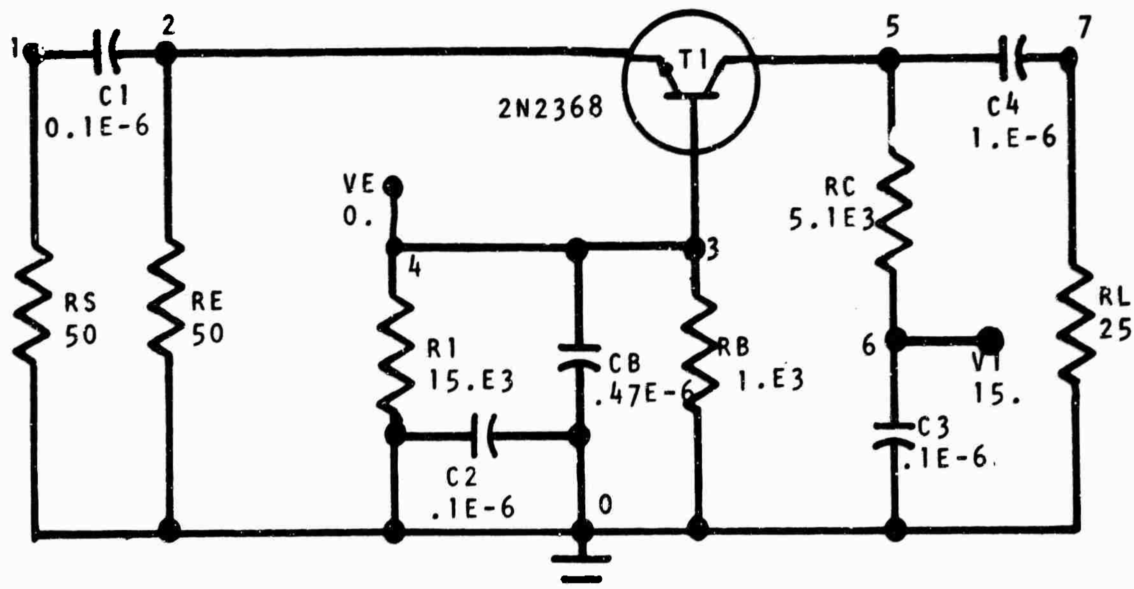
$V_e = 12.35,$ $I_{pp} = 52.0 \times 10^{-6}$

$V_e = 14.5,$ $I_{pp} = 33.0 \times 10^{-6}$

$V_e = 16.0$ $I_{pp} = 17.0 \times 10^{-6}$

The values of V_e correspond to those used during the experimental transient-radiation testing of the circuit.

Figure 49 shows the circuit diagram. The CIRCUS input is given in Table V. The computer results are shown in figures 50 and 51.



Values in volts, ohms, and farads

Figure 49. Common-Base Amplifier with no Compensation

TABLE V

CIRCUS Input for a Common-Base Amplifier with no Compensation

```
DEVICE PARAMETERS
TRANSISTOR,2N2368,NPN,RB,30.,RC,20.,RE,.01,A1,5.25E-12,
PHI1,1.,N1,.31,
A2,3.18E-12,PHI2,.9,N2,.1,IES,1.29E-15,ICS,1.45E-13,
THETAN,40.2,THETAI,29.7
BN,.01,40.
BI,.01,.1
TCN,.01,4.1E-10
TCI,.01,9.E-8
END
   COMMON-BASE AMPLIFIER-NO COMPENSATION  VE = 0.
T1,3,5,2,2N2368
VE,0,4,0.
V1,0,6,15.
RL,0,7,25.
RC,6,5,5.1E3
RB,0,3,1.E3
R1,4,3,15.E3
RE,0,2,50.
RS,0,1,50.
C1,1,2,.1E-6
C2,0,4,.1E-6
CB,0,3,.47E-6
C3,0,6,.1E-6
C4,7,5,1.E-6
PHOTOCURRENT,2N2368,IPP,1.E8,0.,70.E-9,
0.,10.E-9,30.E-9,50.E-9,70.E-9,
0.,0.,65.E-6,65.E-6,0.
PEAK RATE,1.E9,1.E10
PRINT,VN2,VN3,VN5,VN7
INTERVALS,10.E-9,490.E-9
EXECUTE
```

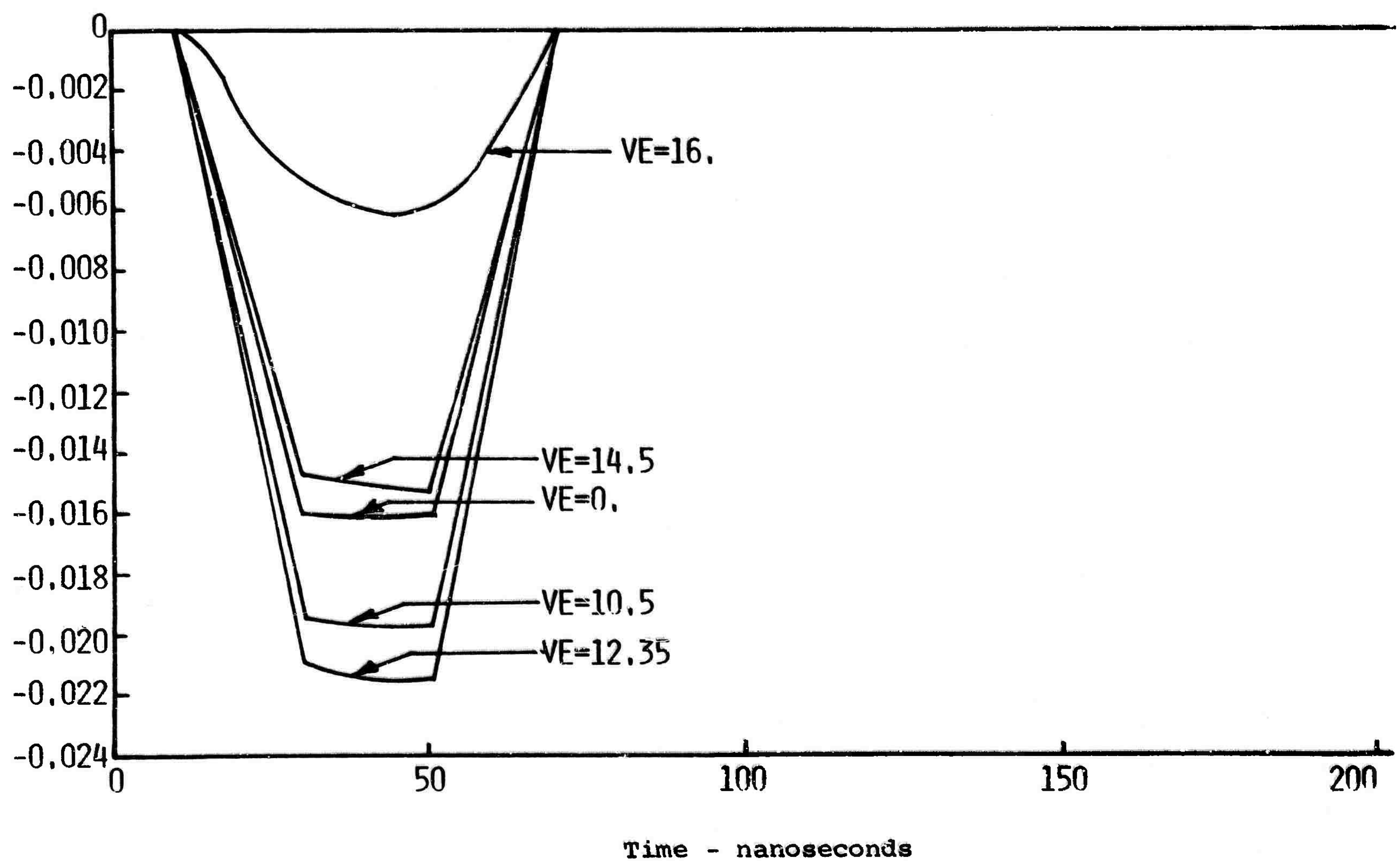


Figure 50. Common-Base Amplifier with no Compensation, $\dot{\gamma} = 10^9$ R/sec

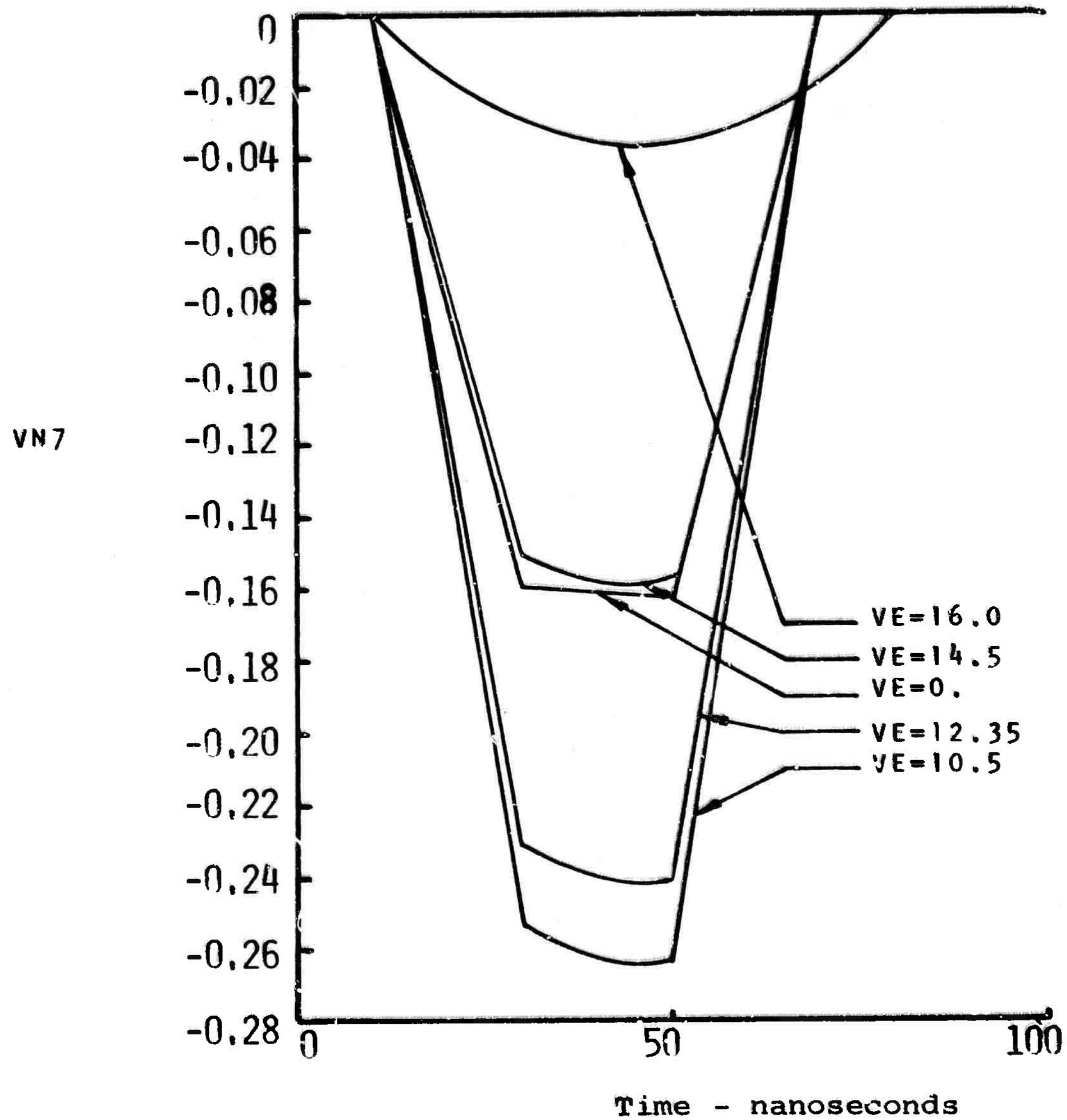


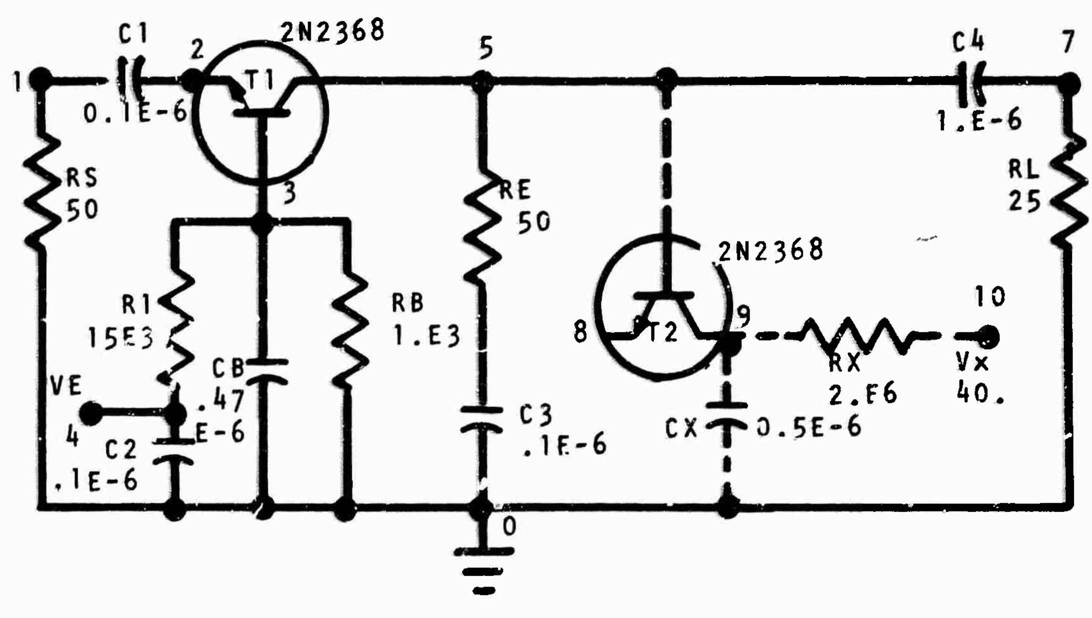
Figure 51. Common-Base Amplifier with no Compensation, $\dot{\gamma} = 10^{10}$ R/sec

6. Computer Results for a Common-Base Amplifier with Collector-to-Ground Compensation

A collector-to-ground compensation junction is now added to the circuit just analyzed. I_{pp} is varied (for both T1 and T2) with changes of V_e in the same manner as previously described.

Figure 52 shows the circuit diagram. The CIRCUS input is given in Table VI.

The resulting output plots are shown in figures 53 and 54. The output is reduced as compared to that of figures 50 and 51. A slight increase in compensation current would yield further reduction (see equations (44), (45), and (46)).



Values in volts, ohms, and farads

Figure 52. Common-Base Amplifier with Collector-to-Ground Compensation

TABLE VI

CIRCUS Input for a Common-Base Amplifier with Collector-to-Ground Compensation

```
DEVICE PARAMETERS
TRANSISTOR,2N2368,NPN,RB,30.,RC,20.,RE,.01,A1,5.25E-12,
PHI1,1.,N1,.31,
A2,3.18E-12,PHI2,.9,N2,.1,IES,1.29E-15,ICS,1.45E-13,
THETAN,40.2,THETAI,29.7
BN,.01,40.
BI,.01,.1
TCN,.01,4.1E-10
TCI,.01,9.E-8
END
   COMMON-BASE AMPLIFIER-COLLECTOR GROUND COMPENSATION  VE = 0.
T1,3,5,2,2N2368
T2,5,9,8,2N2368
VX,0,10,40.
VE,0,4,0.
V1,0,6,15.
RX,9,10,2.E6
RL,0,7,25.
RC,6,5,5.1E3
RB,0,3,1.E3
R1,4,3,15.E3
RE,0,2,50.
RS,0,1,50.
CX,0,9,.5E-6
C1,1,2,.1E-6
C2,0,4,.1E-6
CB,0,3,.47E-6
C3,0,6,.1E-6
C4,7,5,1.E-6
PHOTOCURRENT,2N2368,IPP,1.E8,0.,70.E-9,
0.,10.E-9,30.E-9,50.E-9,70.E-9,
0.,0.,65.E-6,65.E-6,0.
PEAK RATE,1.E9,1.E10
PRINT,VN2,VN3,VN5,VN7
INTERVALS,10.E-9,490.E-9
EXECUTE
```

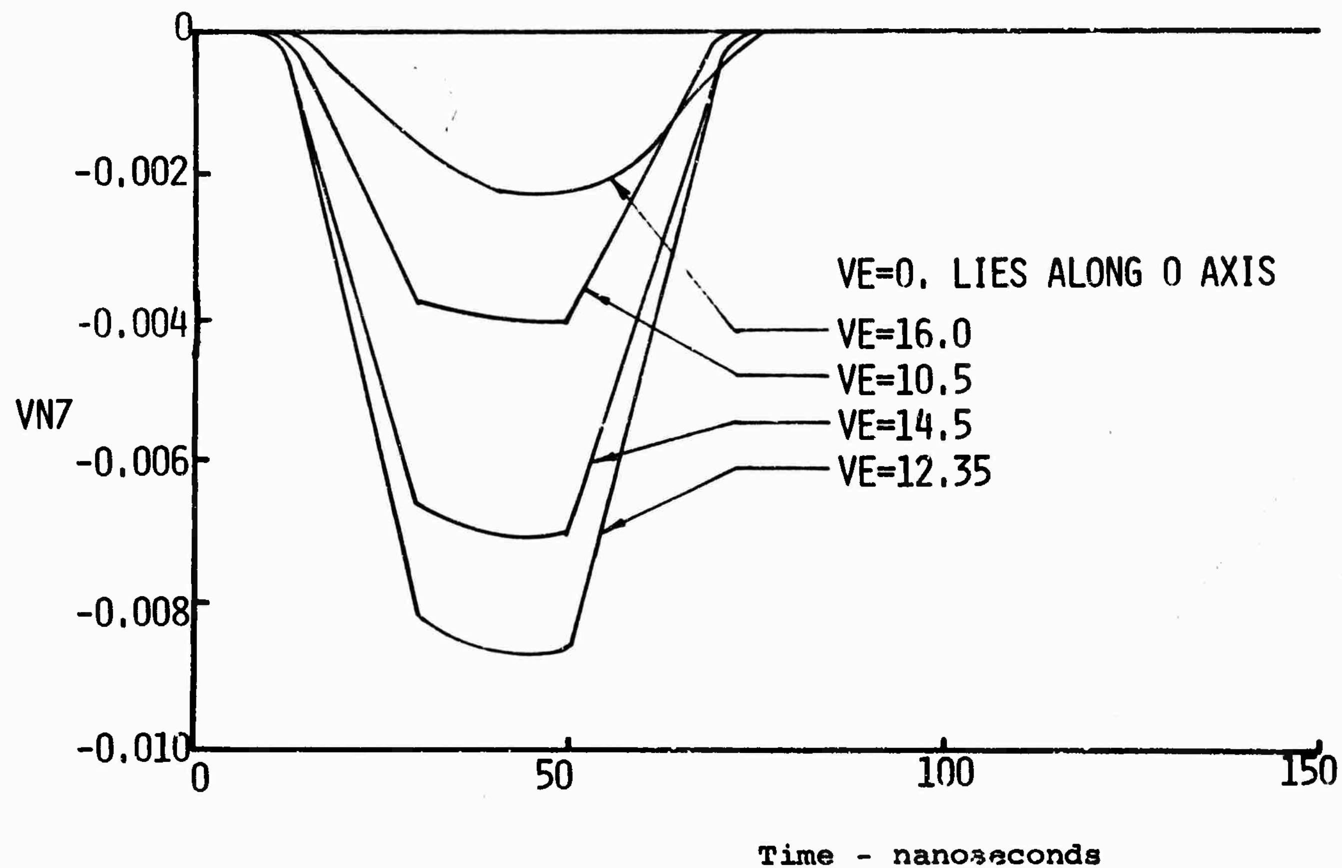


Figure 53. Common-Base Amplifier with Collector-to-Ground Compensation, $\dot{\gamma} = 10^9$ R/sec

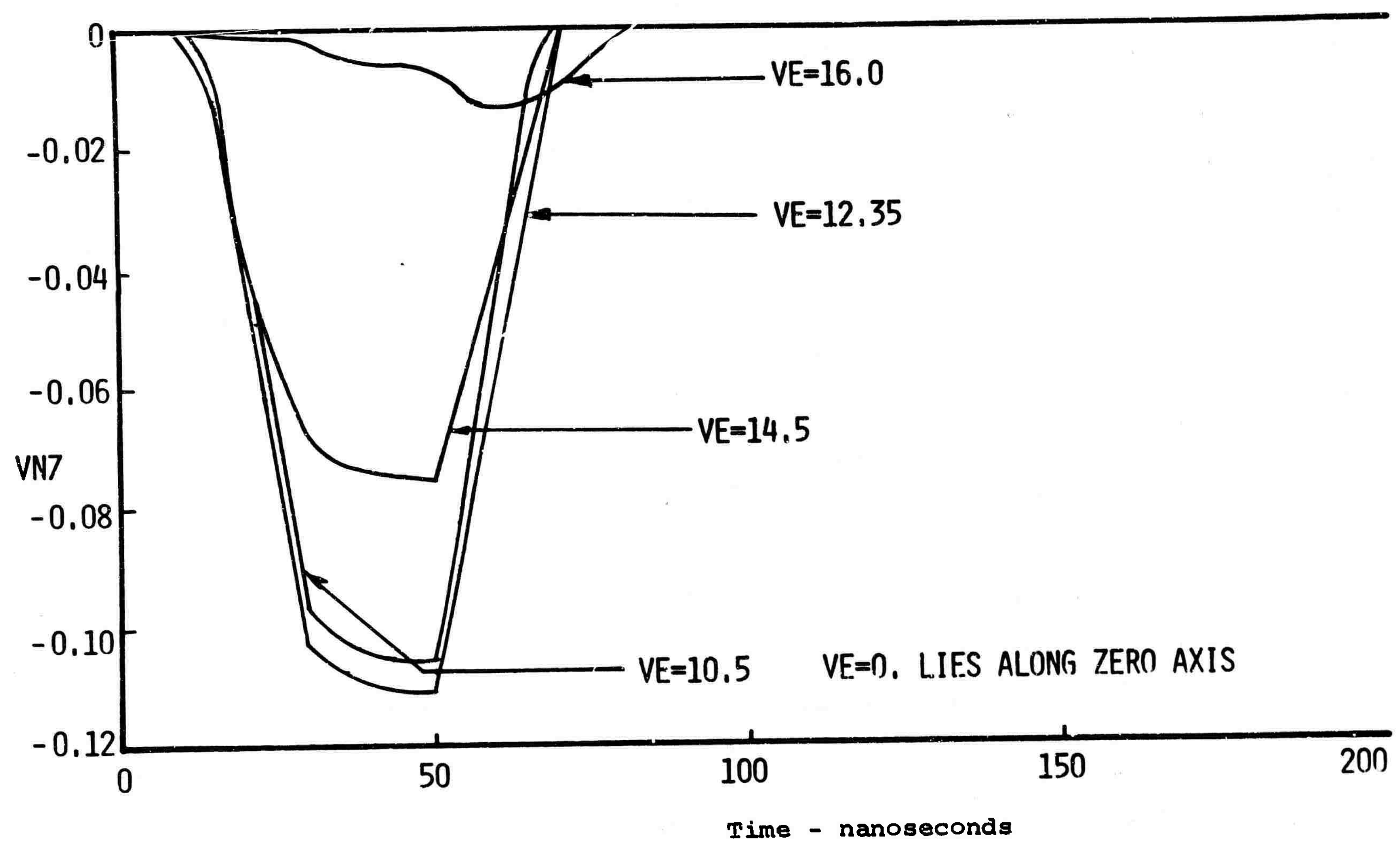


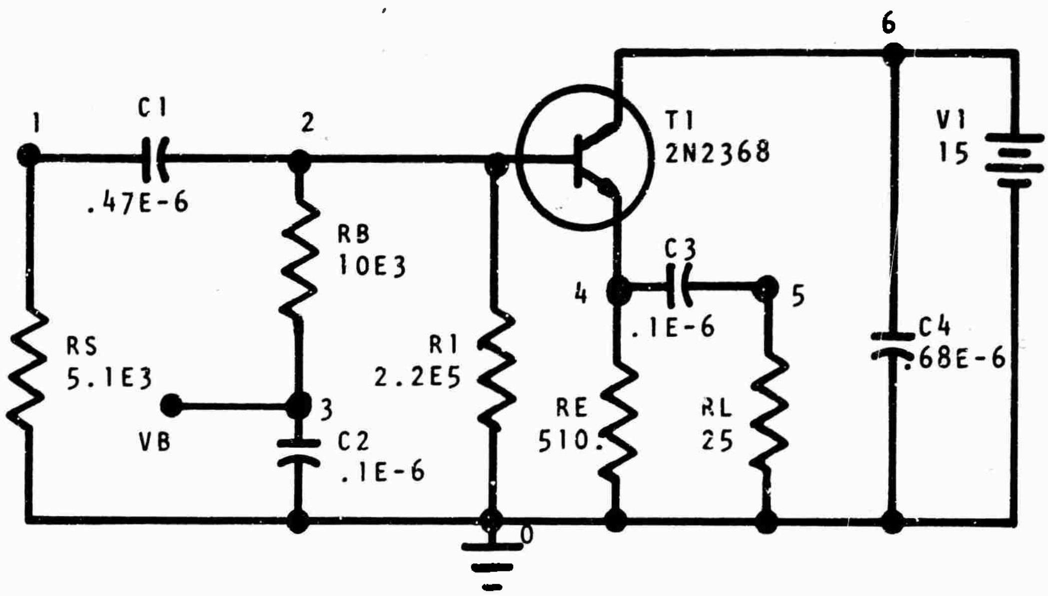
Figure 54. Common-Base Amplifier with Collector-to-Ground Compensation, $\dot{\gamma} = 10^{10}$ R/sec

7. Computer Results for an Emitter-Follower Amplifier with no Compensation

The results for the basic emitter-follower amplifier with no compensation is given. As the collector-to-base voltage of this amplifier does not change drastically with change of the input bias level, I_{pp} of 60 μa was used. This value is appropriate for the use of a V_{cc} of 15 volts.

The circuit diagram is shown in figure 55. The CIRCUS input is given in Table VII.

The resulting plots are shown in figures 56 and 57.



Values in volts, ohms, and farads

Figure 55. Emitter Follower with no Compensation

TABLE VII

CIRCUS Input for an Emitter-Follower Amplifier with no Compensation

```
   EMITTER FOLLOWER-NO COMPENSATION
DEVICE PARAMETERS
TRANSISTOR,2N2368,NPN,RB,30.,RC,20.,RE,.01,A1,5.25E-12,
PHI1,1.,N1,.31,
A2,3.18E-12,PHI2,.9,N2,.1,IES,1.29E-15,ICS,1.45E-13,
THETAN,40.2,THETAI,29.7
BN,.01,40.
BI,.01,.1
TCN,.01,4.1E-10
TCI,.01,9.E-8
END
T1,2,6,4,2N2368
V1,0,6,15.
VB,0,3,0.
C4,0,6,.68E-6
C3,4,5,.1E-6
C2,0,3,.1E-6
C1,1,2,.47E-6
RL,0,5,25.
RE,0,4,510.
R1,0,2,2.2E5
RB,3,2,10.E3
RS,0,1,5.1E3
PHOTOCURRENT,2N2368,IPP,1.E8,0.,70.E-9,
0.,10.E-9,30.E-9,50.E-9,70.E-9,
0.,0.,60.E-6,60.E-6,0.
PEAK RATE,1.E9,1.E10
PRINT,VN2,VN4,VN5
INTERVALS,10.E-9,490.E-9
EXECUTE
```

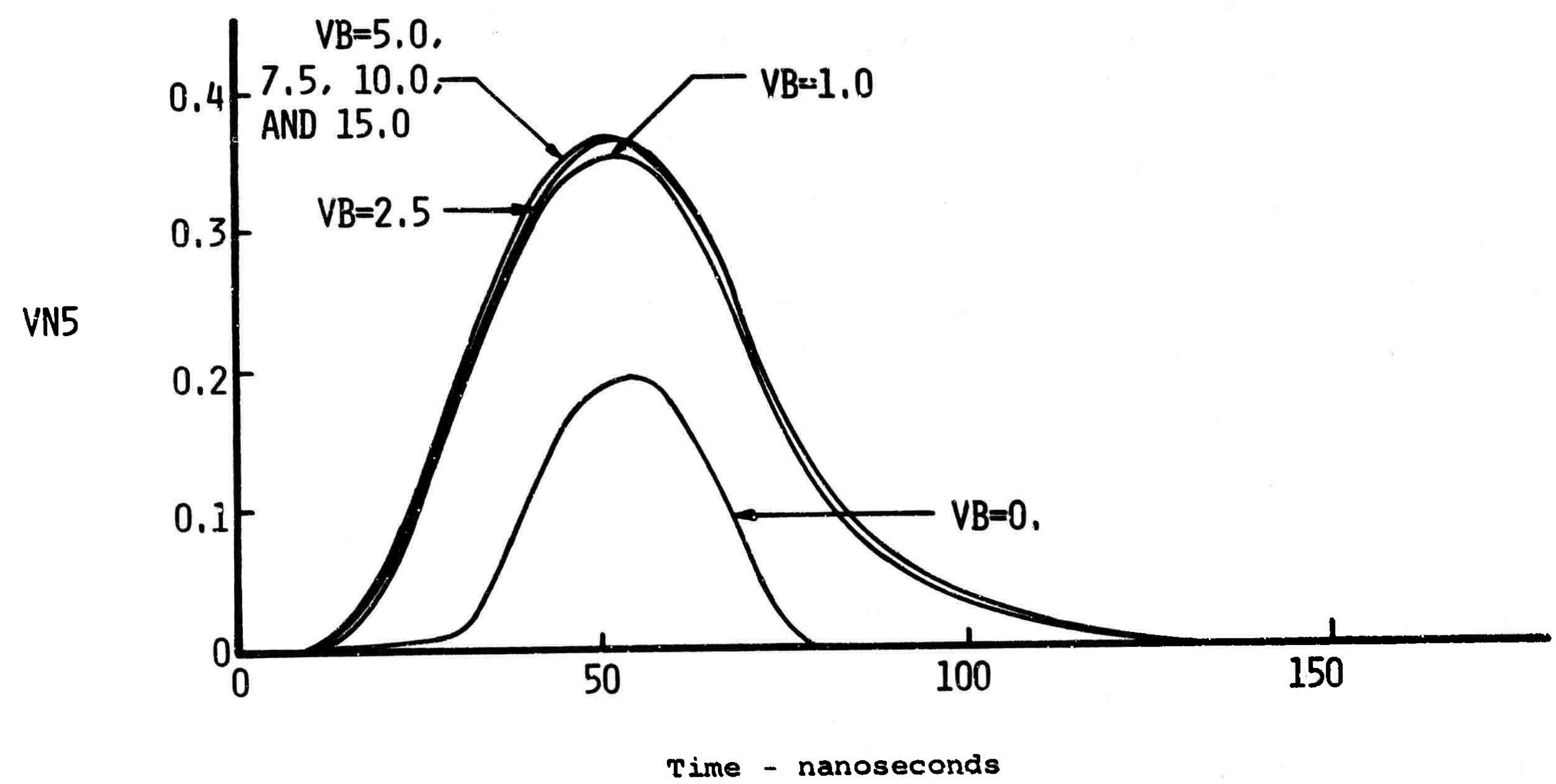


Figure 56. Emitter-Follower Amplifier with no Compensation, $\dot{\gamma} = 10^9$ R/sec

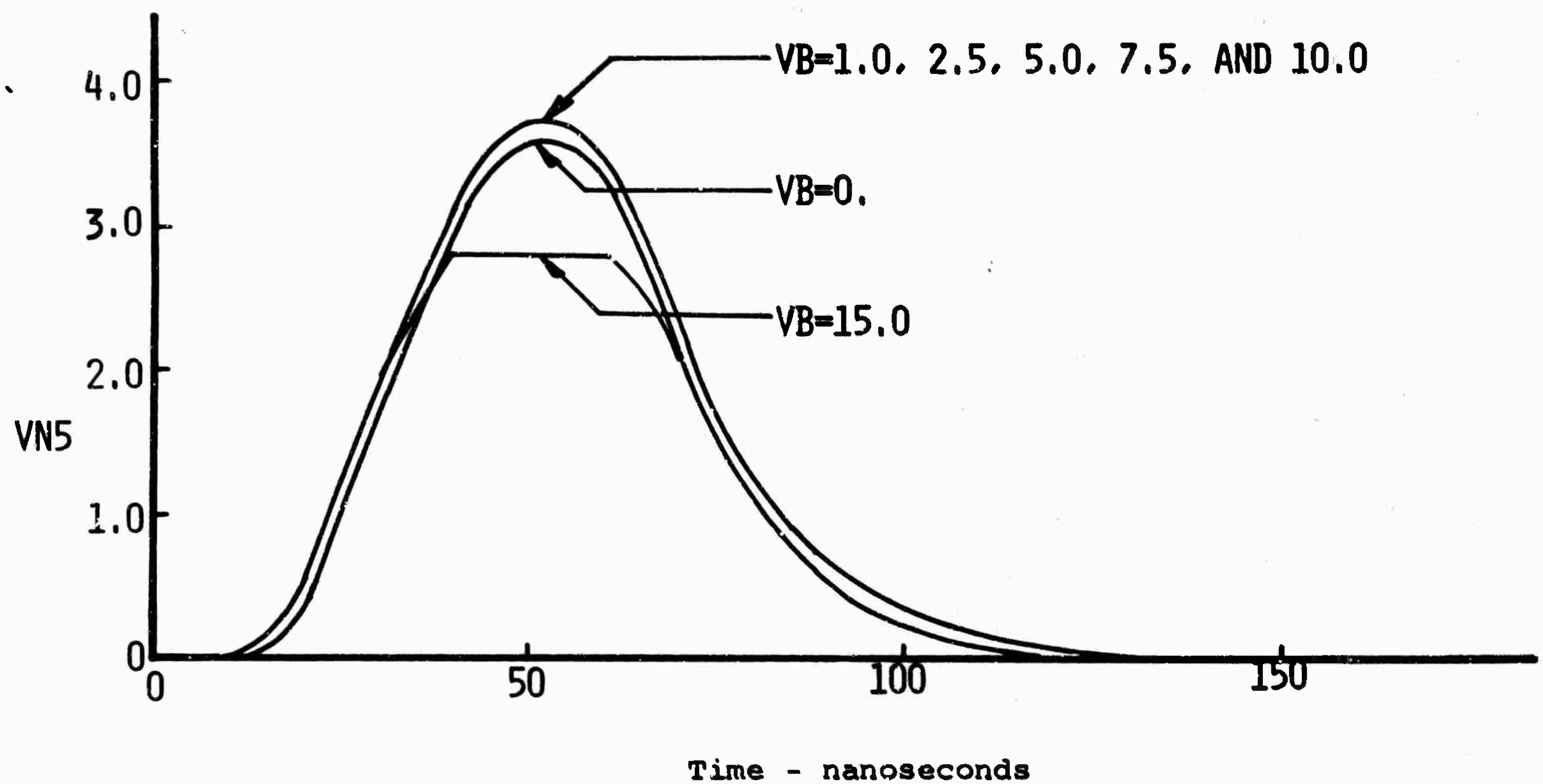


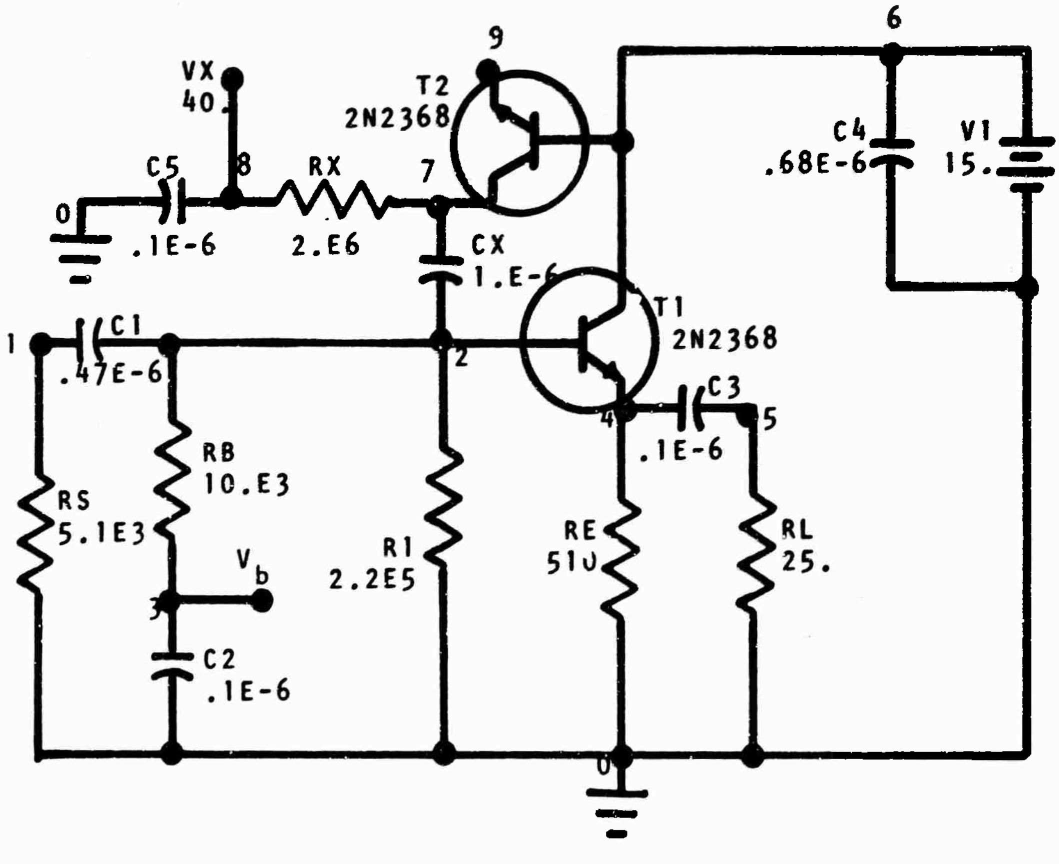
Figure 57. Emitter-Follower Amplifier with no Compensation, $\dot{\gamma} = 10^{10}$ R/sec

8. Computer Results for an Emitter-Follower Amplifier with Collector-to-Base Compensation

A compensation junction is added to the basic emitter-follower amplifier from the collector to the base of T1.

The circuit diagram is shown in figure 58. The CIRCUS input is given in Table VIII, and the resulting graphs are shown in figures 59 and 60.

Note that the compensation has reduced the output by about two orders of magnitude (see figures 56 and 57).



Values in volts, ohms, and farads

Figure 58. Emitter-Follower Amplifier with Collector-to-Base Cancellation

TABLE VIII

CIRCUS Input for an Emitter-Follower Amplifier with Collector-to-Base Compensation

```
   EMITTER FOLLOWER-COLLECTOR TO BASE COMPENSATION
DEVICE PARAMETERS
TRANSISTOR,2N2368,NPN,RB,30.,RC,20.,RE,.01,A1,5.25E-12,
PHI1,1.,N1,.31,
A2,3.18E-12,PHI2,.9,N2,.1,IES,1.29E-15,ICS,1.45E-13,
THETAN,40.2,THETAI,29.7
BN,.01,40.
BI,.01,.1
TCN,.01,4.1E-10
TCI,.01,9.E-8
END
T1,2,6,4,2N2368
T2,6,7,9,2N2368
VB,0,3,7.5
V1,0,6,15.
VX,0,8,40.
RL,0,5,25.
RE,0,4,510.
R1,0,2,2.2E5
RB,3,2,10.E3
RS,0,1,5.1E3
RX,7,8,2.E6
C4,0,6,.68E-6
C3,5,4,.1E-6
C2,0,3,.1E-6
C1,1,2,.47E-6
CX,2,7,1.E-6
C5,0,8,.1E-6
PHOTOCURRENT,2N2368,IPP,1.E8,0.,70.E-9,
0.,10.E-9,30.E-9,50.E-9,70.E-9,
0.,0.,60.E-6,60.E-6,0.
PEAK RATE,1.E9,1.E10
PRINT,VN2,VN4,VN5
INTERVALS,10.E-9,490.E-9
EXECUTE
```

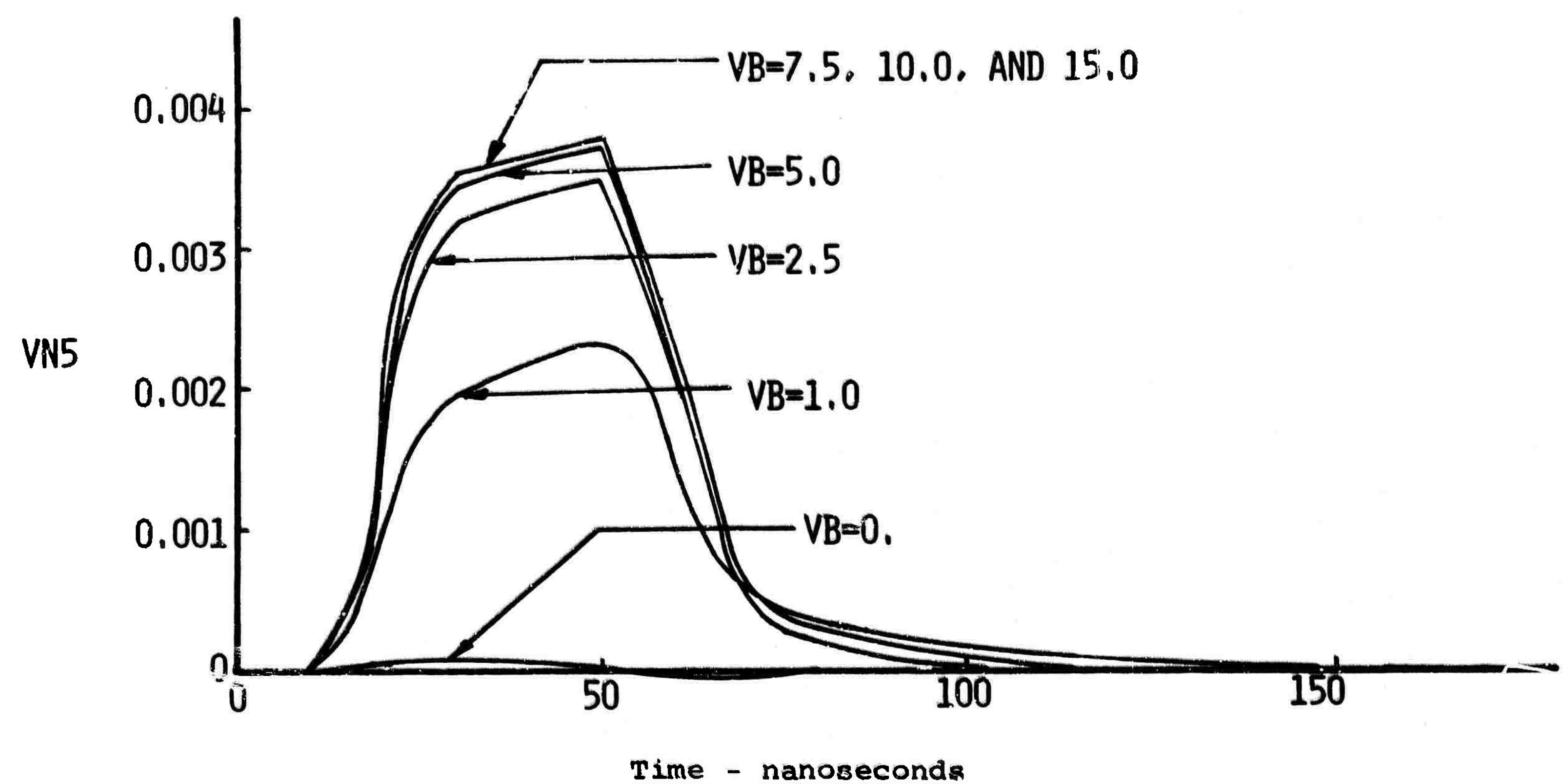


Figure 59. Emitter-Follower Amplifier with Collector-to-Base Compensation, $\dot{\gamma} = 10^9$ R/sec

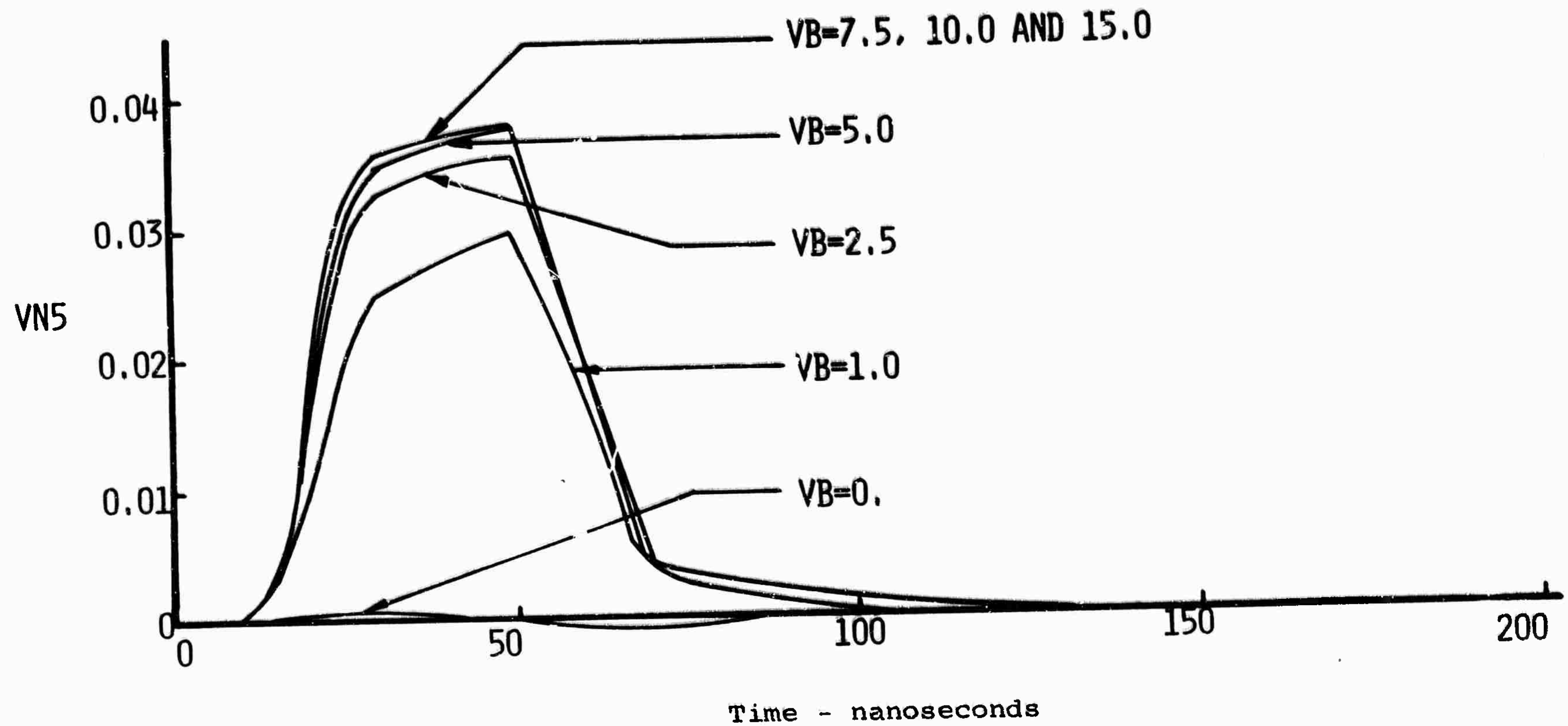
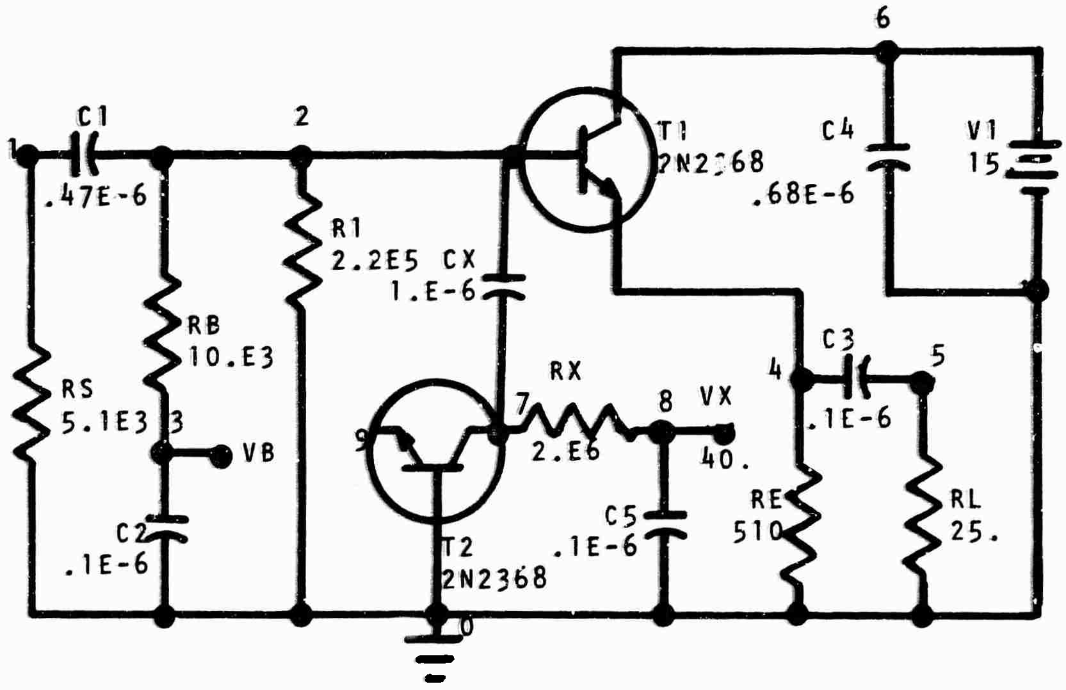


Figure 60. Emitter-Follower Amplifier with Collector-to-Base Compensation, $\dot{\gamma} = 10^{10}$ R/sec

9. <u>Computer Results for an Emitter-Follower Amplifier with Base-to-Ground Compensation</u>

The next circuit analyzed is similar to the preceding one. A compensation junction is added from the base of T1 to ground. For short pulses, the preceding circuit and the present circuit are equivalent. These computer computations were made to confirm that this was correct. The resulting computer calculations indicated very little difference in the two methods of compensation.

The circuit diagram is shown in figure 61. The CIRCUS input is given in Table IX. The output plots of the results are shown in figures 62 and 63.



Values in ohms, volts and farads

Figure 61. Emitter-Follower Amplifier with Base-to-Ground Compensation

TABLE IX

CIRCUS Input for an Emitter-Follower Amplifier with Base-to-Ground Compensation

```
   EMITTER FOLLOWER-BASE TO GROUND COMPENSATION
DEVICE PARAMETERS
TRANSISTOR,2N2368,NPN,RB,30.,RC,20.,RE,.01,A1,5.25E-12,
PHI1,1.,N1,.31,
A2,3.18E-12,PHI2,.9,N2,.1,IES,1.29E-15,ICS,1.45E-13,
THETAN,40.2,THETAI,29.7
BN,.01,40.
BI,.01,.1
TCN,.01,4.1E-10
TCI,.01,9.E-8
END
T1,2,6,4,2N2368
T2,0,7,9,2N2368
V1,0,6,15.
VB,0,3,7.5
VX,0,8,40.
C4,0,6,0.68E-6
C3,5,4,.1E-6
C5,0,8,.1E-6
CX,7,2,1.E-6
C2,0,3,.1E-6
C1,2,1,.47E-6
RL,0,5,25.
RE,0,4,510.
RX,7,8,2.E6
R1,0,2,2.2E5
RB,3,2,10.E3
RS,0,1,5.1E3
PHOTOCURRENT,2N2368,IPP,1.E8,0.,70.E-9,
0.,10.E-9,30.E-9,50.E-9,70.E-9,
0.,0.,60.E-6,60.E-6,0.
PEAK RATE,1.E9,1.E10
PRINT,VN2,VN4,VN5,VN6
INTERVALS,10.E-9,490.E-9
EXECUTE
```

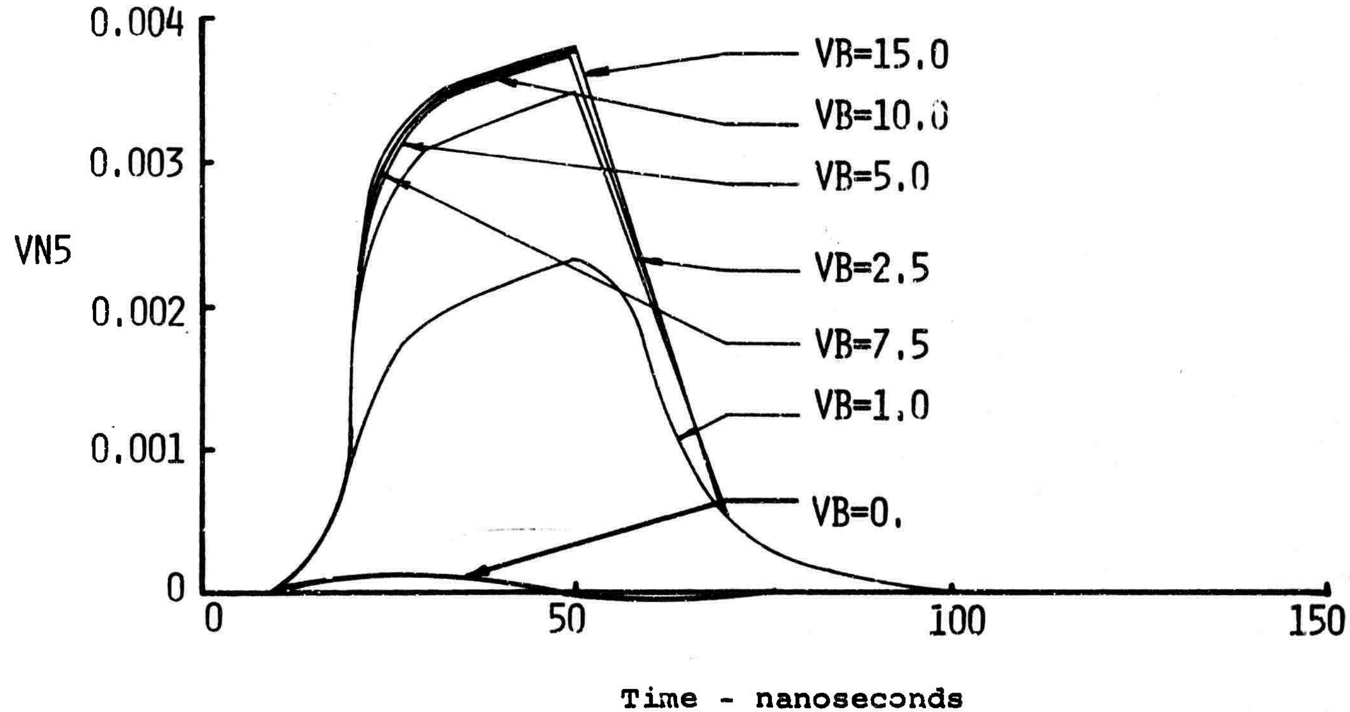


Figure 62. Emitter-Follower Amplifier with Base-to-Ground Compensation, $\dot{\gamma} = 10^9$ R/sec

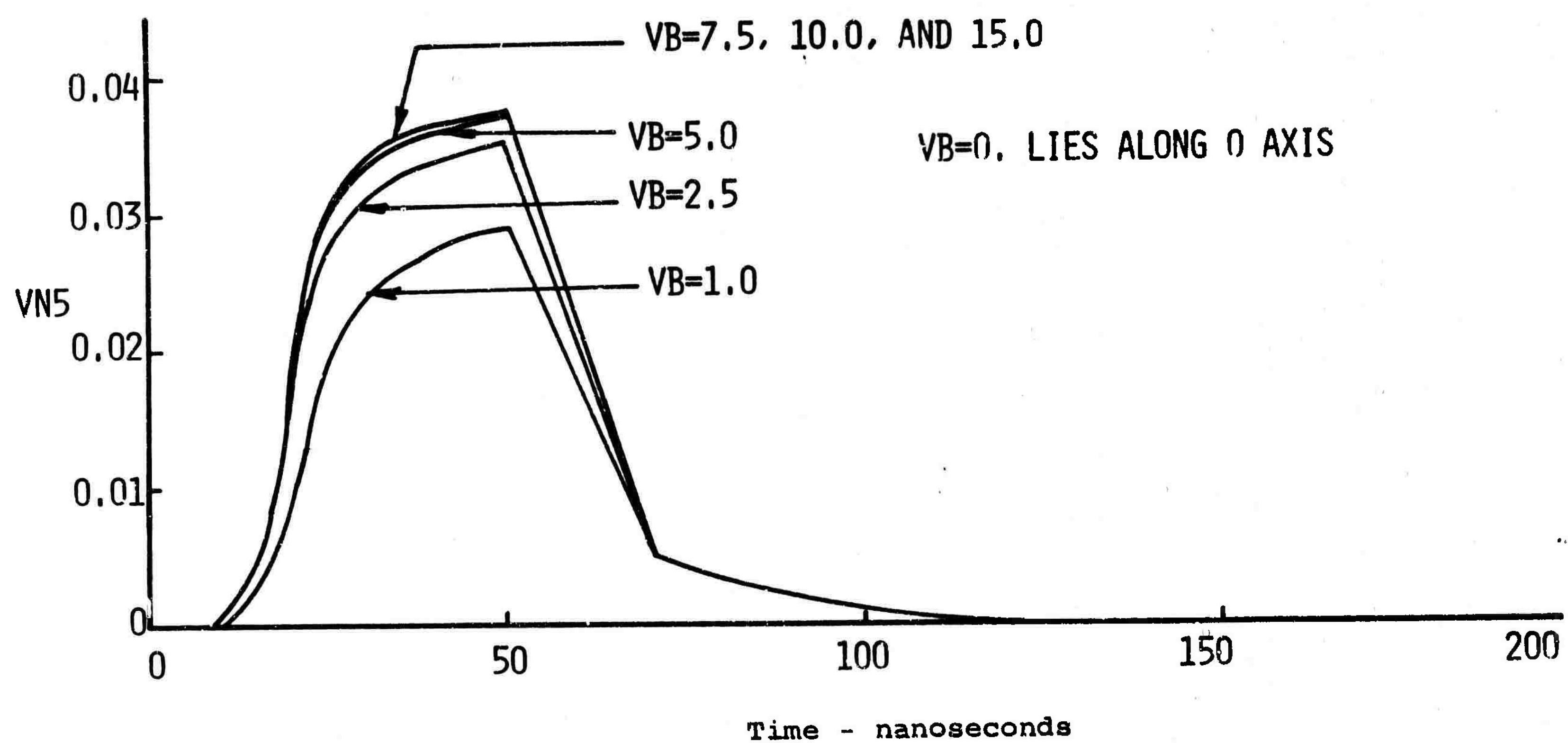


Figure 63. Emitter-Follower Amplifier with Base-to-Ground Compensation, $\dot{\gamma} = 10^{10}$ R/sec

10. Computer Results for a Common-Base Amplifier Driving a Common-Collector Amplifier

A circuit diagram is shown in figure 64 for a common-base amplifier followed by a common-collector amplifier. Capacitor coupling is used between stages so that individual biasing of the two amplifiers is possible by varying VE and VB, respectively, for the common-base and the common-collector stages. This was done because of the interest in determining the degree of inherent compensation present for different combinations of cutoff, active, and saturation regions of operation for the two amplifier stages. Computer computations were made for all the combinations of

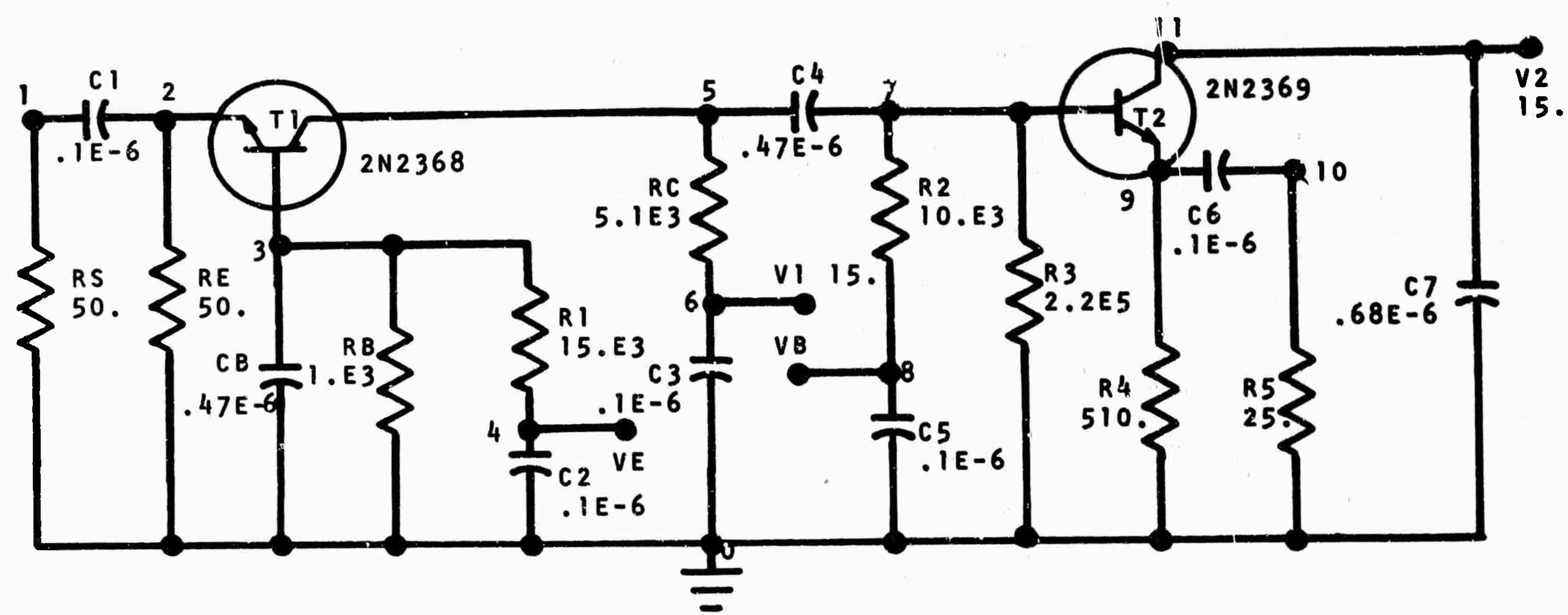
VE = 0, 10.5, 12.35, 14.5, and 16.0

VB = 0, 1, 2.5, 5, 7.5, 10, and 15

The method of presenting the data is for VE to be held constant for one value while VB is varied as a discrete parameter. The CIRCUS input listing is shown in Table X. Note also that I_{pp} is varied with VE as described in section IV-5.

The resulting graphs of the circuit output voltage, VNIO, are shown in the following figures.

VE = 0.0	figures 65 and 66
VE = 10.5	figures 67 and 68
VE = 12.35	figures 69 and 70
VE = 14.5	figures 71 and 72
VE = 16.0	figures 73 and 74



Values in ohms, volts, and farads

Figure 64. Common-Base Amplifier Driving a Common-Collector Amplifier

TABLE X

CIRCUS Input for a Common-Base Amplifier Driving a Common-Collector Amplifier

```
DEVICE PARAMETERS
TRANSISTOR,2N2368,NPN,RB,30.,RC,20.,RE,.01,A1,5.25E-12,
PHI1,1.,N1,.31,
A2,3.18E-12,PHI2,.9,N2,.1,IES,1.29E-15,ICS,1.45E-13,
THETAN,40.2,THETAI,29.7
BN,.01,40.
BI,.01,.1
TCN,.01,4.1E-10
TCI,.01,9.E-8
TRANSISTOR,2N2369,NPN,RB,30.,RC,20.,RE,.01,A1,5.25E-12,
PHI1,1.,N1,.31,
A2,3.18E-12,PHI2,.9,N2,.1,IES,1.29E-15,ICS,1.45E-13,
THETAN,40.2,THETAI,29.7
BN,.01,40.
BI,.01,.1
TCN,.01,4.1E-10
TCI,.01,9.E-8
END
   CB-CC  VE = 0.
T1,3,5,2,2N2368
T2,7,11,9,2N2369
V2,0,11,15.
VB,0,8,7.5
V1,0,6,15.
VE,0,4,0.
RS,0,1,50.
RE,0,2,50.
RB,0,3,1.E3
R1,3,4,15.E3
RC,5,6,5.1E3
R2,8,7,10.E3
R3,0,7,2.2E5
R4,0,9,510.
R5,0,10,25.
C1,1,2,.1E-6
CB,0,3,.47E-6
C2,0,4,.1E-6
C3,0,6,.1E-6
C4,5,7,.47E-6
C5,0,8,.1E-6
C6,9,10,.1E-6
C7,0,11,.68E-6
PHOTOCURRENT,2N2368,IPP,1.E8,0.,70.E-9,
0.,10.E-9,30.E-9,50.E-9,70.E-9,
0.,0.,65.E-6,65.E-6,0.
PHOTOCURRENT,2N2369,IPP,1.E8,0.,70.E-9,
0.,10.E-9,30.E-9,50.E-9,70.E-9,
0.,0.,60.E-6,60.E-6,0.
PEAK RATE, 1.E9,1.E10
PRINT,VN2,VN3,VN5,VN7,VN9,VN10
INTERVALS,10.E-9,490.E-9
EXECUTE
```

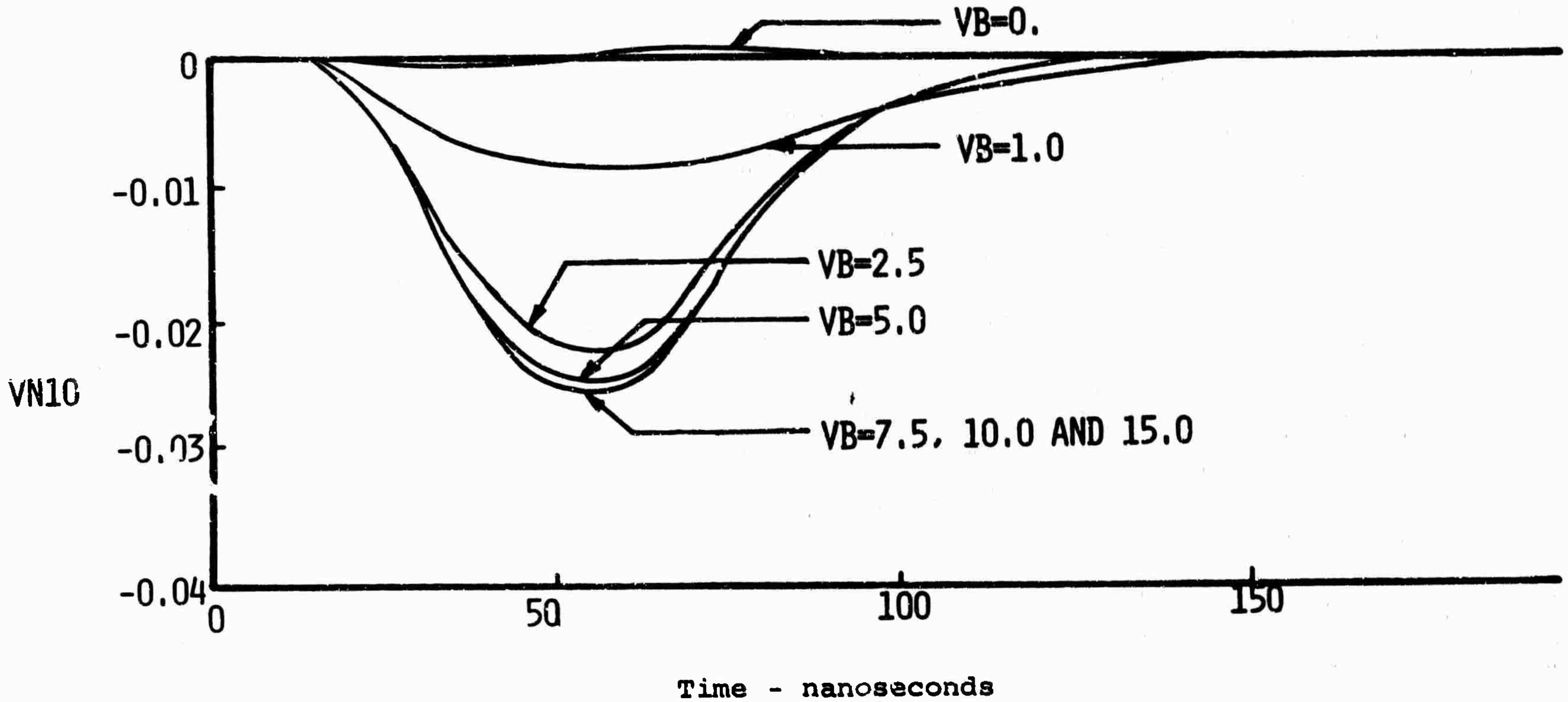


Figure 65. Common-Base to Common-Collector Amplifier, VE=0, $\dot{\gamma}=10^9$ R/sec

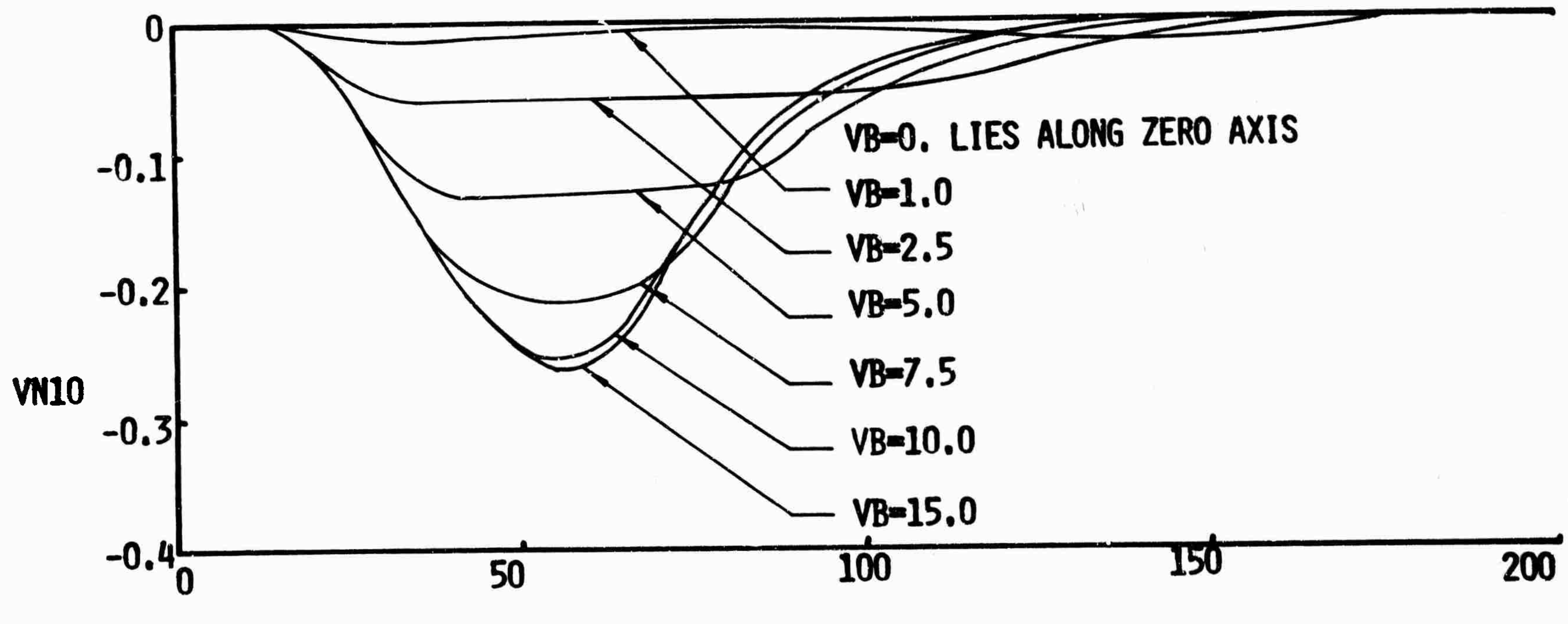


Figure 66. Common-Base to Common-Collector Amplifier, VE=0, $\dot{\gamma}=10^{10}$ R/sec

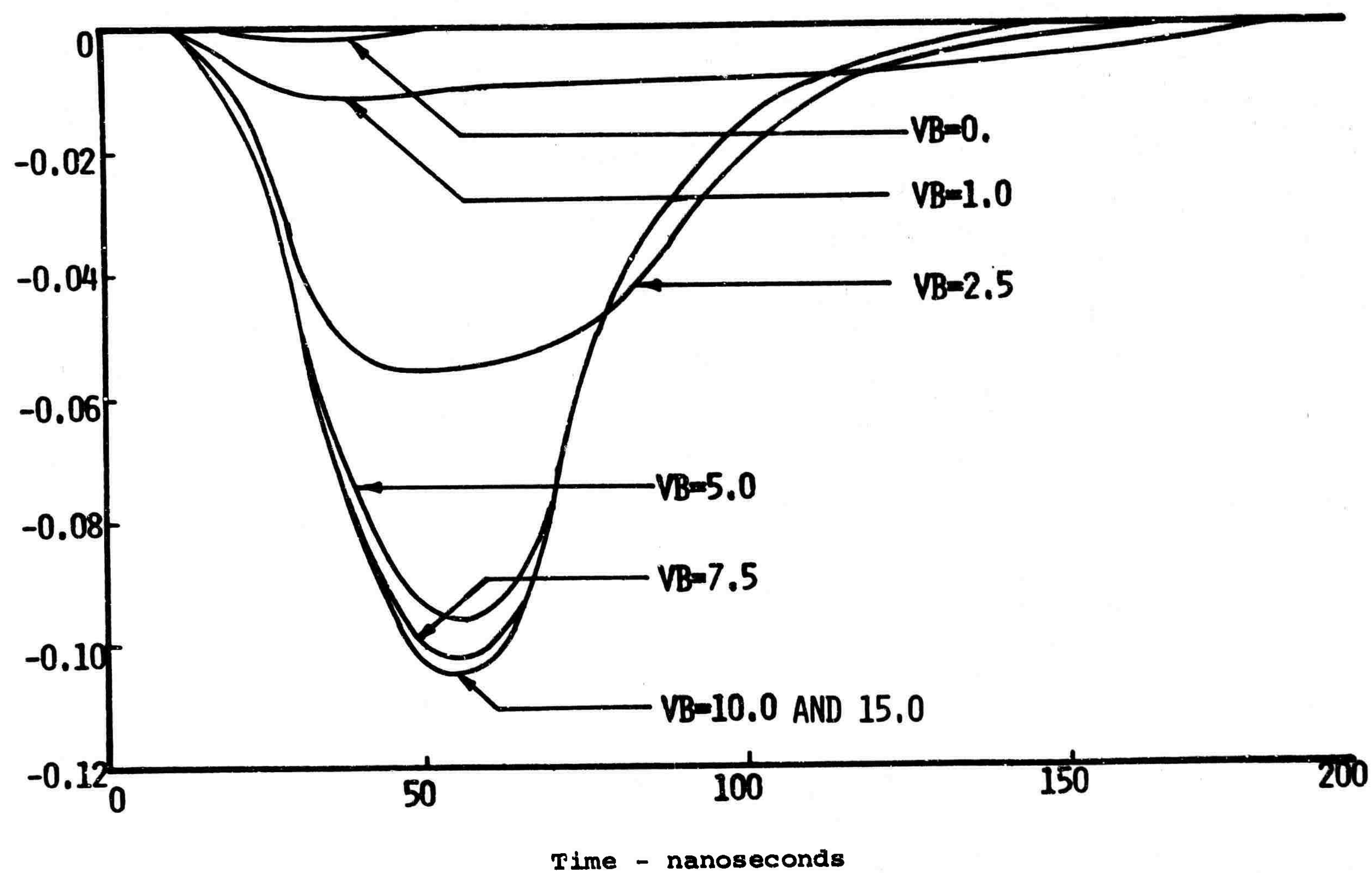


Figure 67. Common-Base to Common-Collector Amplifier, VE=10.5, $\dot{\gamma}=10^9$ R/sec

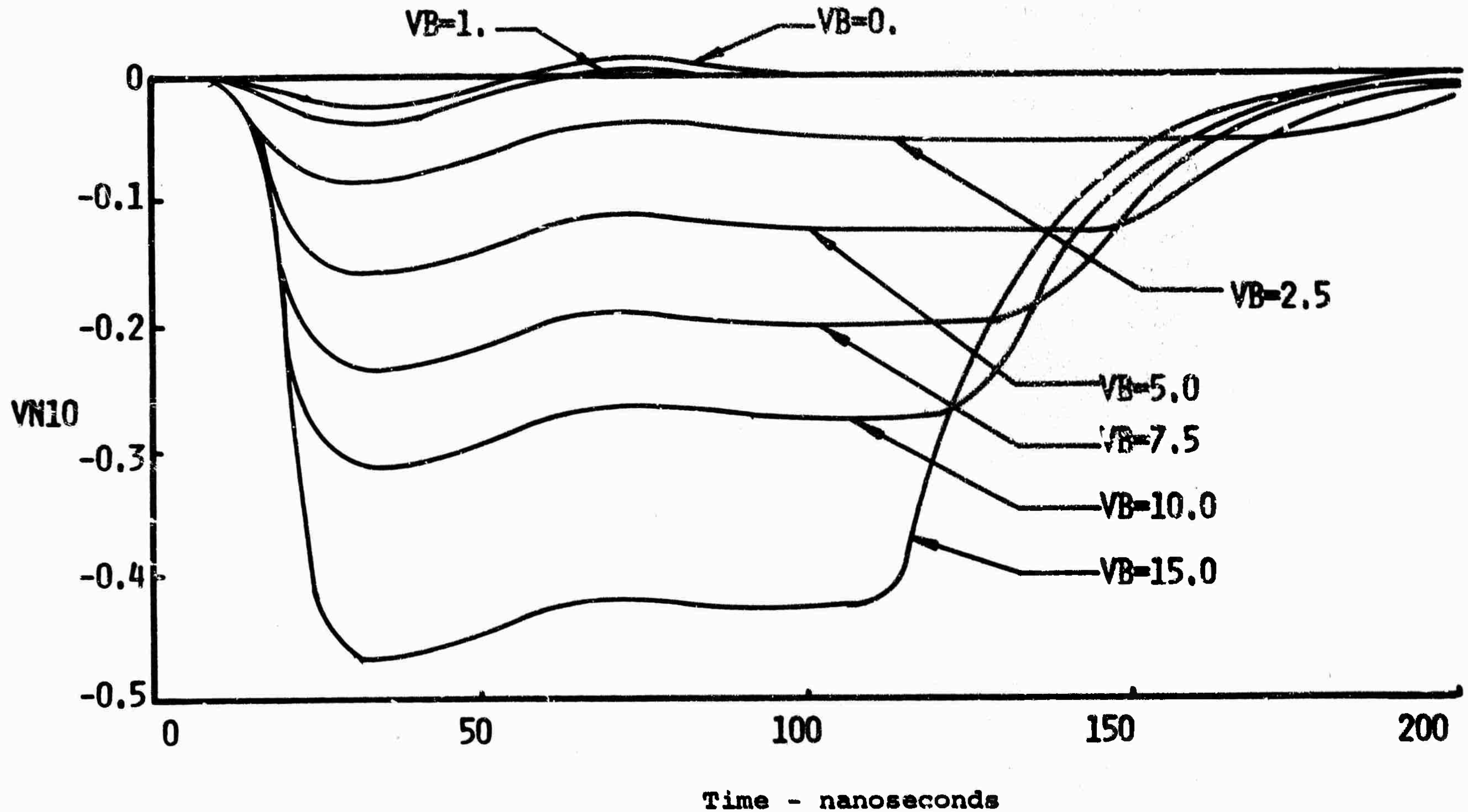


Figure 68. Common-Base to Common-Collector Amplifier, VE=10.5, $\dot{\gamma}=10^{10}$ R/sec

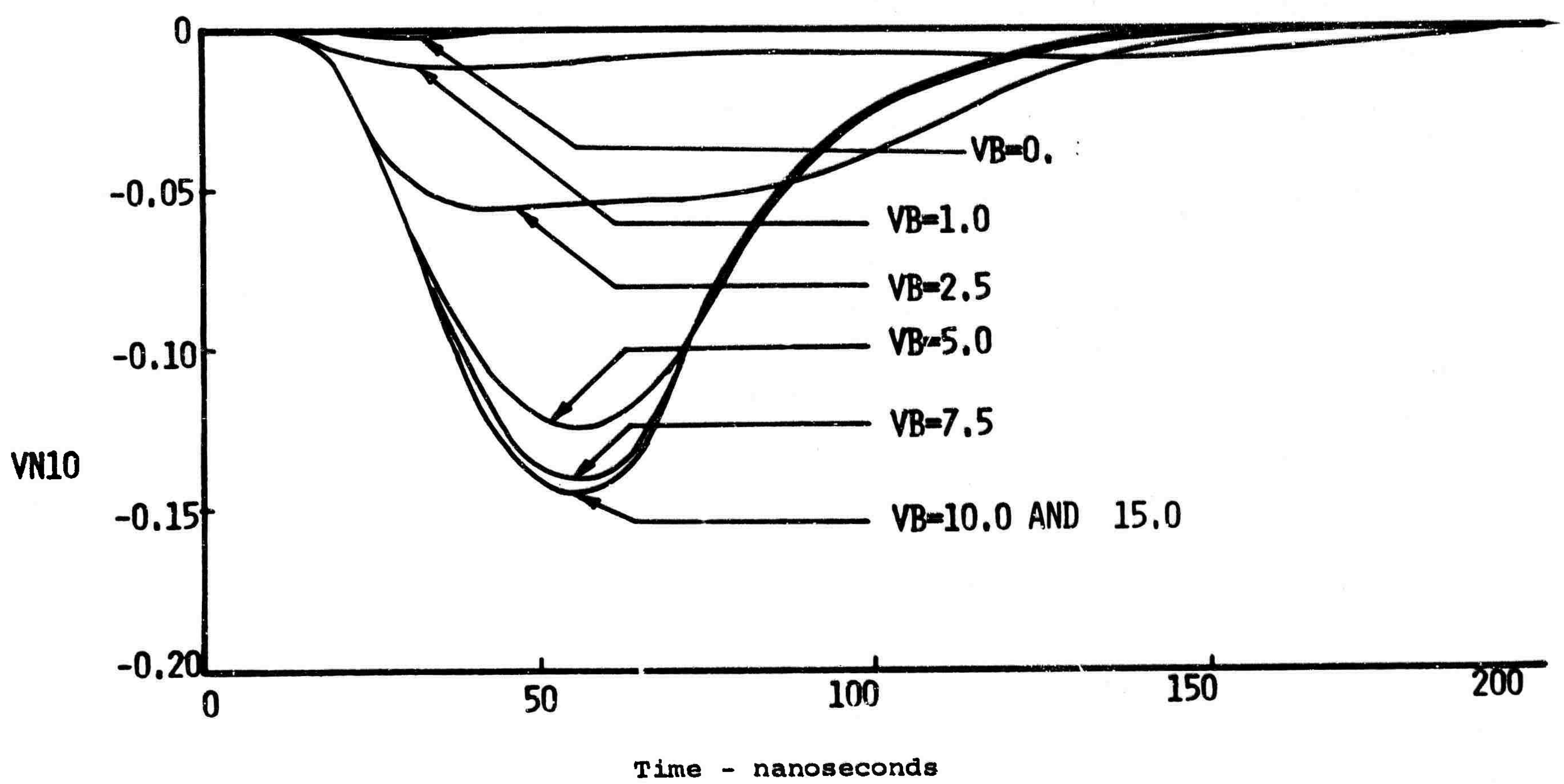


Figure 69. Common-Base to Common-Collector Amplifier, VE=12.35, $\dot{\gamma}=10^9$ R/sec

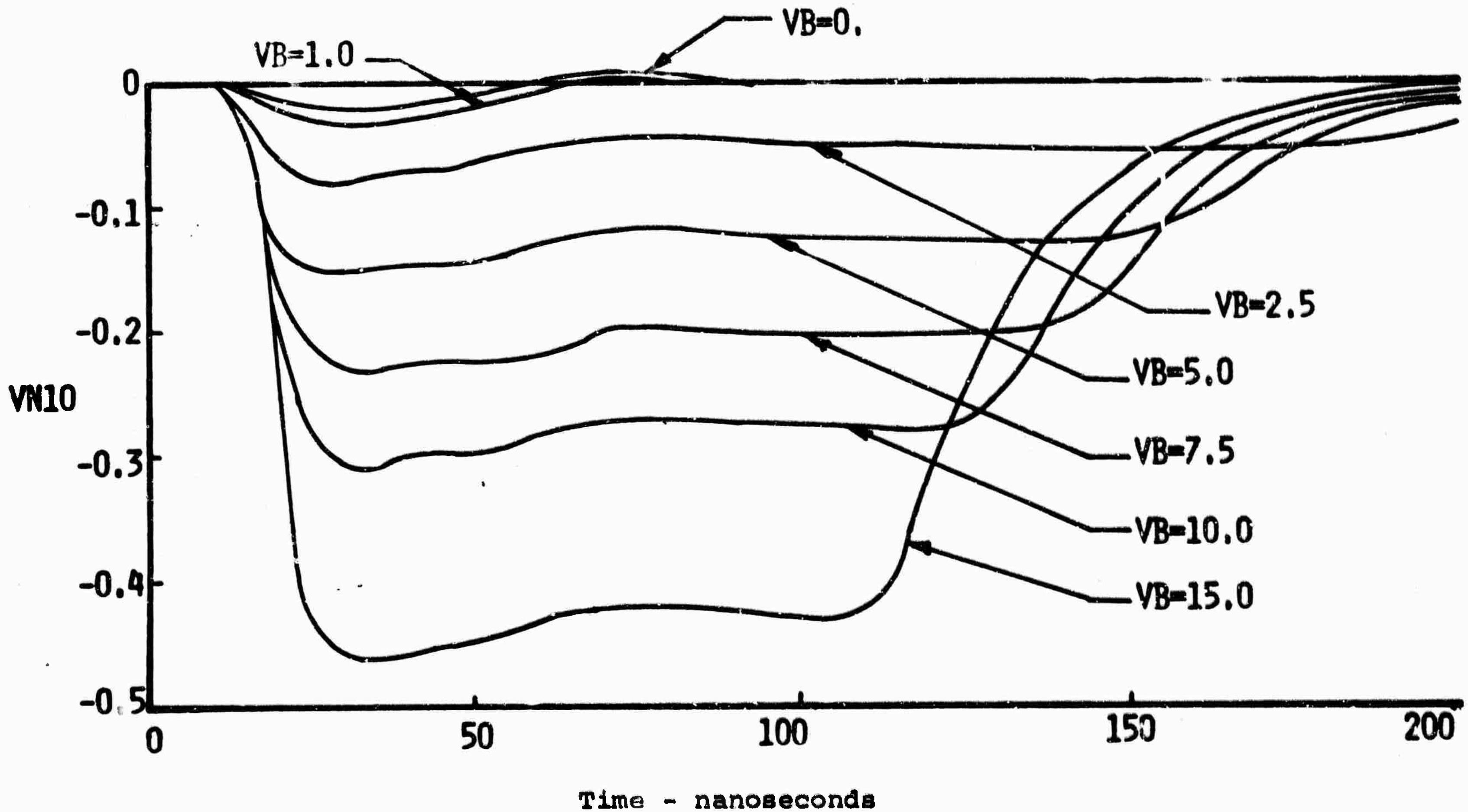


Figure 70. Common-Base to Common-Collector Amplifier, VE=12.35, $\dot{\gamma}=10^{10}$ R/sec

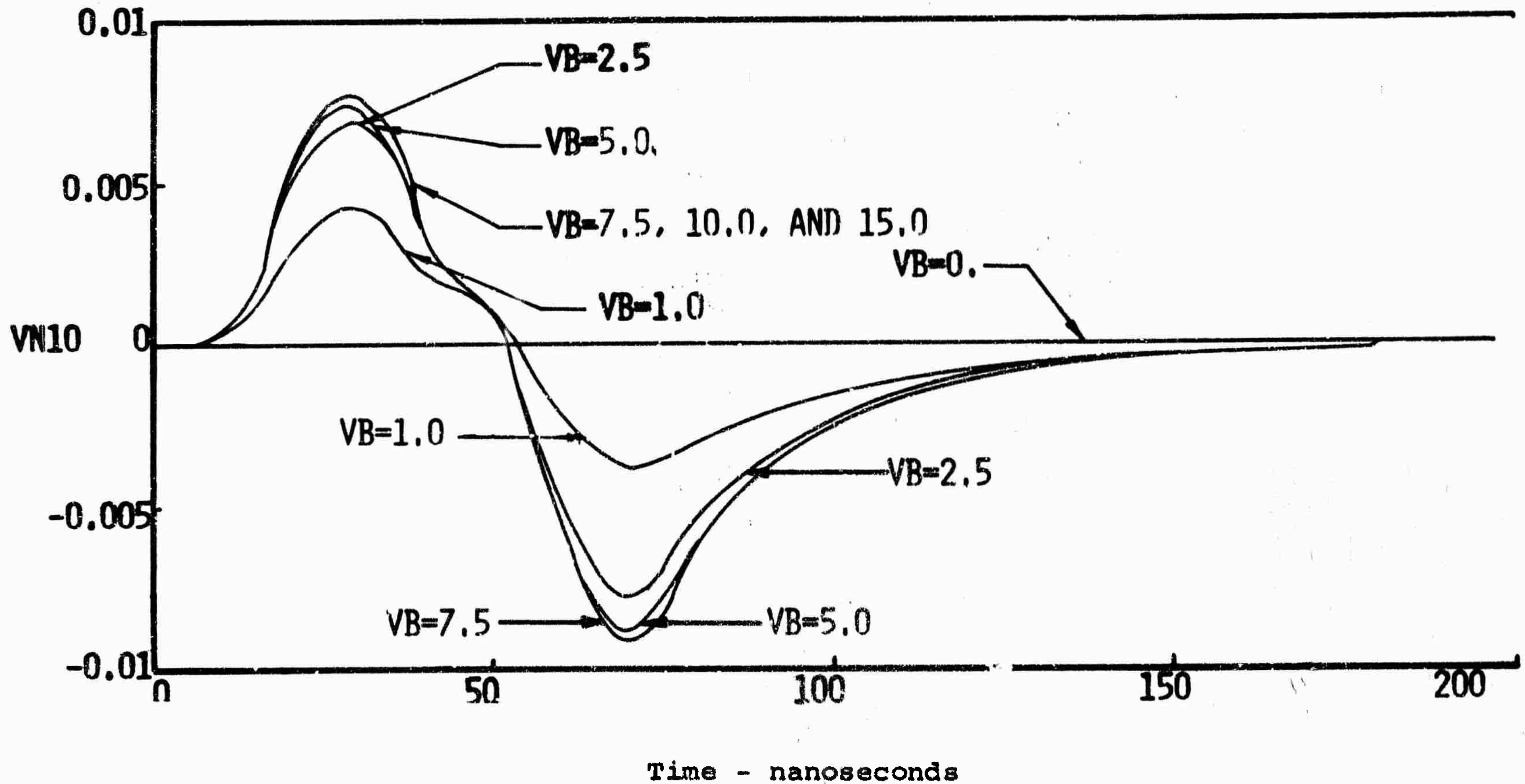


Figure 71. Common-Base to Common-Collector Amplifier, VE=14.5, $\dot{\gamma}=10^9$ R/sec

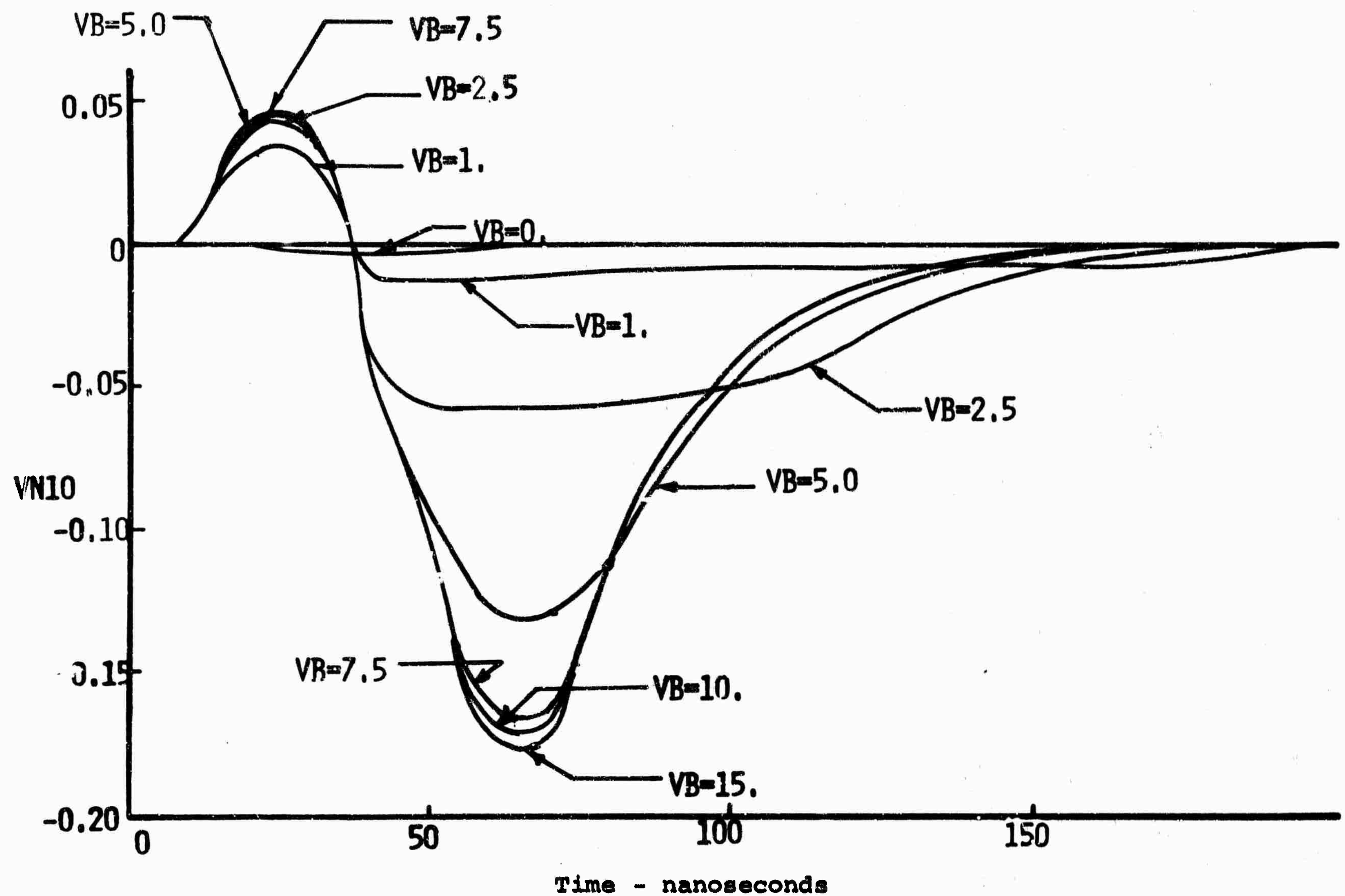


Figure 72. Common-Base to Common-Collector Amplifier, VE=14.5, $\dot{\gamma}=10^{10}$ R/sec

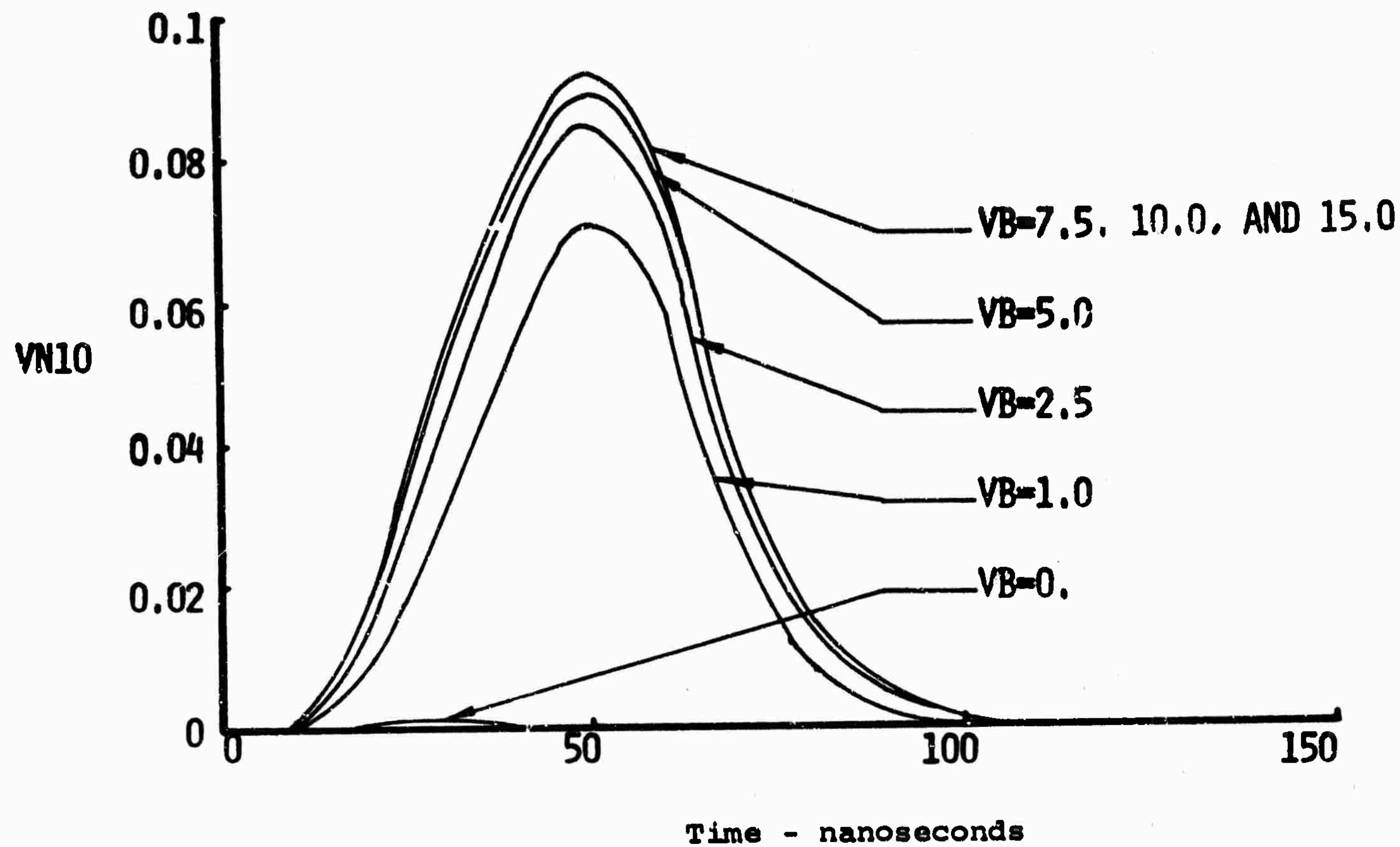


Figure 73. Common-Base to Common-Collector Amplifier, VE=16, $\dot{\gamma}=10^9$ R/sec

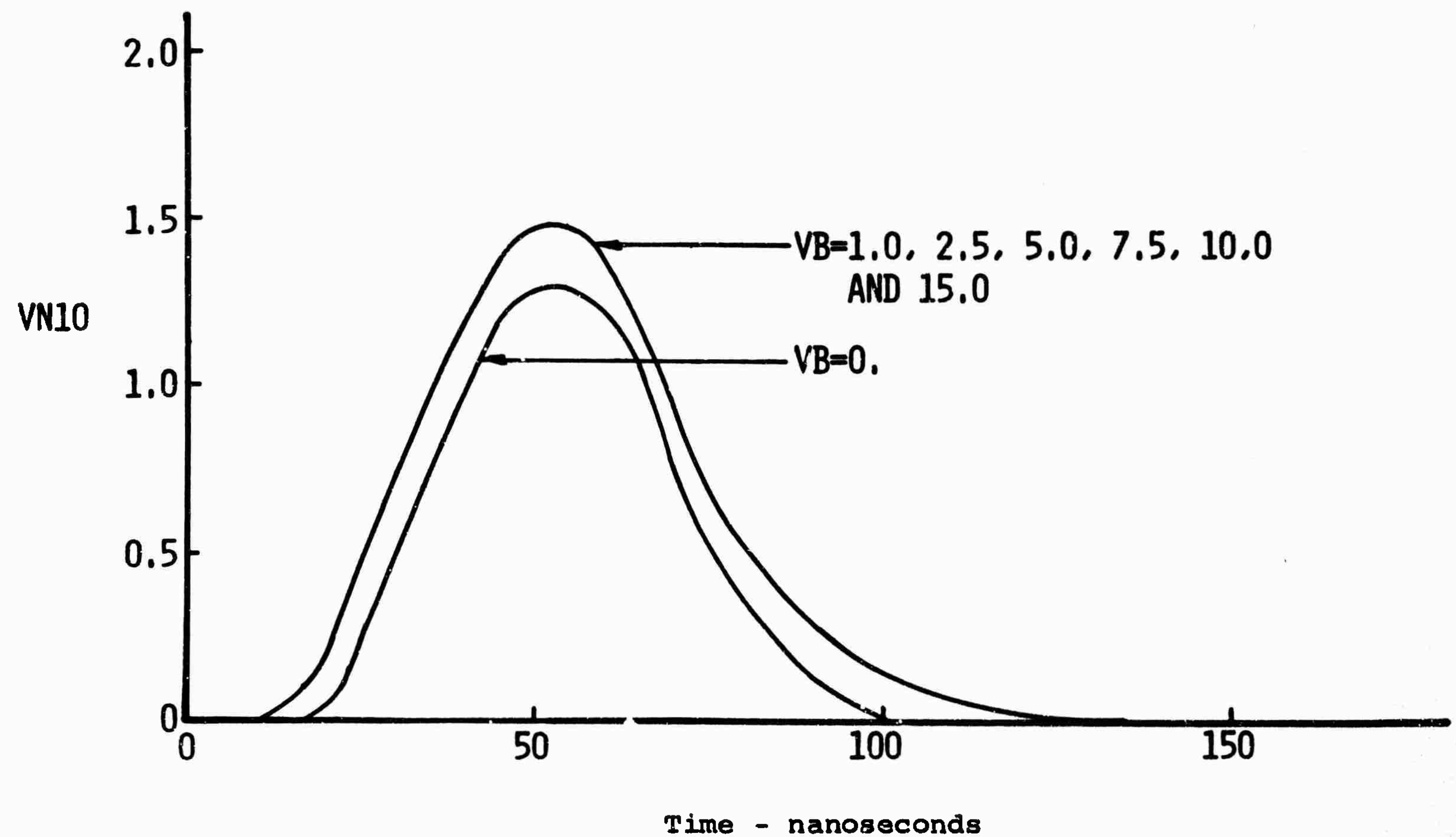


Figure 74. Common-Base to Common-Collector Amplifier, VE=16, $\dot{\gamma}=10^{10}$ R/sec

SECTION V

EXPERIMENTAL TEST RESULTS AND COMPARISONS WITH PREDICTIONS

1. Test Setup and Dosimetry

All the experimental transient irradiation tests were conducted at the Air Force Weapons Laboratory, Kirtland Air Force Base 2 Mev flash X-ray facility. The equipment was the field emission, 2 Mev, flash X-ray system, which has a rated pulse width of 20 nsec. The data were recorded by photographing oscilloscope displays. The oscilloscopes used were the Tektronix Models 517 and 551. The units tested and the instrumentation system were both shielded against stray noise pickup by a double-wall screen room.

The total integrated dose levels that a unit received were adjusted by varying the flash X-ray tube voltage and the distance from the test unit. The dosimetry used consisted of lithium fluoride (L_iF) tablets positioned on the units being irradiated. The total dose in Roentgens (R) was read out on the CON-RAD thermoluminescence dosimetry system*. The approximate dose rates ($\dot{\gamma}$) given with the experimental results were calculated by dividing the total dose in R by the rated X-ray pulse width, 20×10^{-9} sec.

*Model 5100A Readout Instrument, manufactured by Controls for Radiation, Inc.

Only the active device and compensation transistors were exposed to the radiation. The transistors were mounted with the uncut length of the transistor leads so that the transistors projected beyond the shielding into the radiation field. The passive components such as resistors, capacitors, and cables were all carefully shielded from the radiation.

2. Common-Emitter Amplifier.

No Compensation. The circuit diagram for the common-emitter amplifier tested is given in figure 75.

The transient output pulses are shown in figures 76, 77, and 78. Compare these with figures 41 and 42 for the CIRCUS outputs.

Collector-to-Base Compensation. Figure 79 shows the circuit for the common-emitter amplifier with collector-to-base compensation.

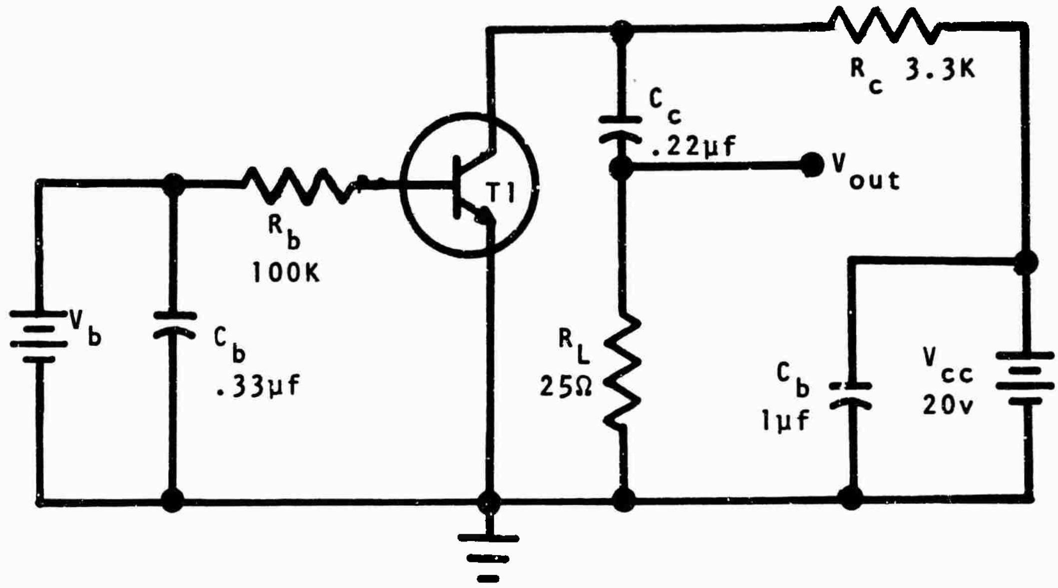


Figure 75. Common-Emitter Amplifier Test Circuit with no Compensation

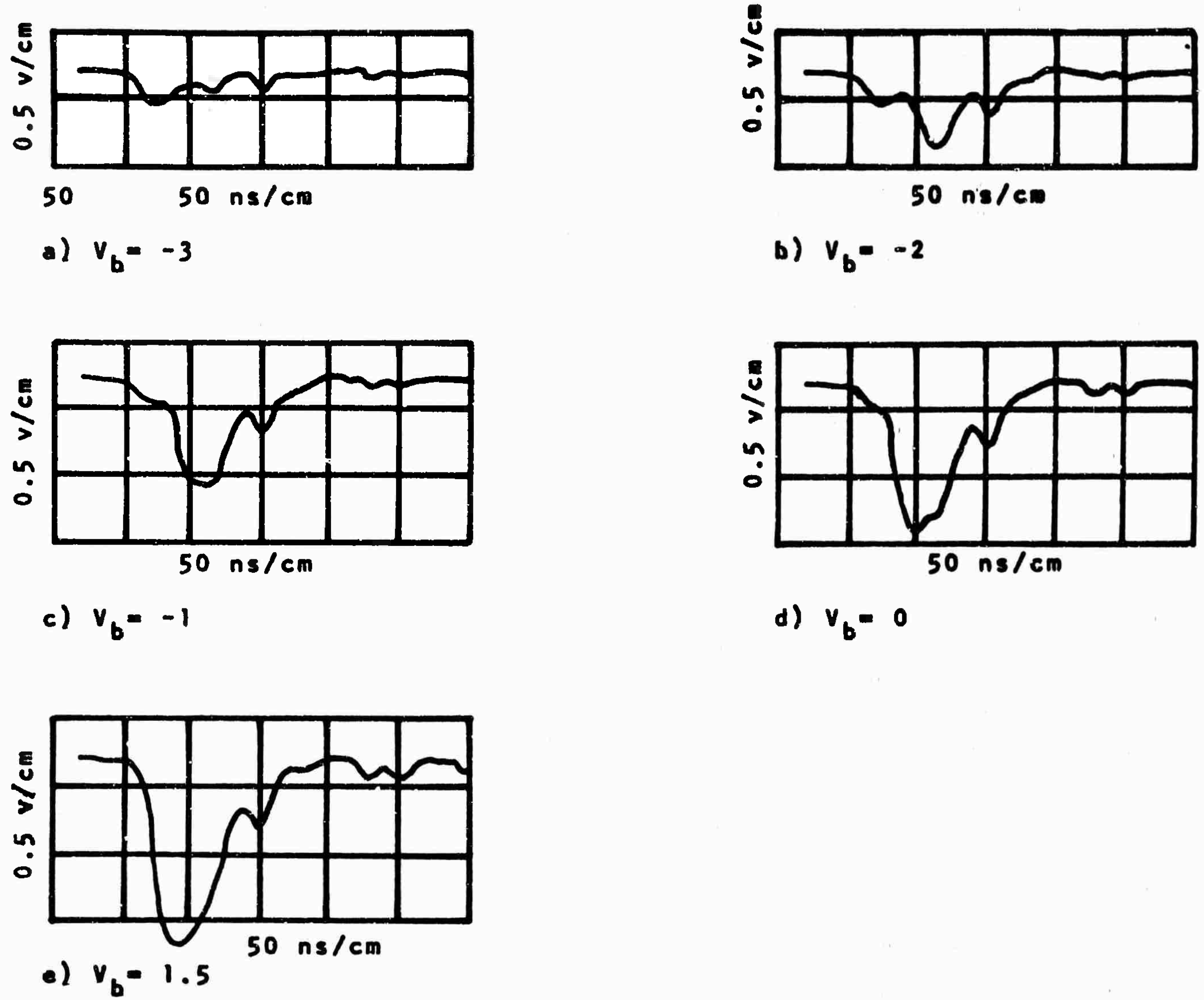


Figure 76. Test Results for Common-Emitter Amplifier with no Compensation, $\dot{\gamma} = 0.625 \times 10^9$ R/sec

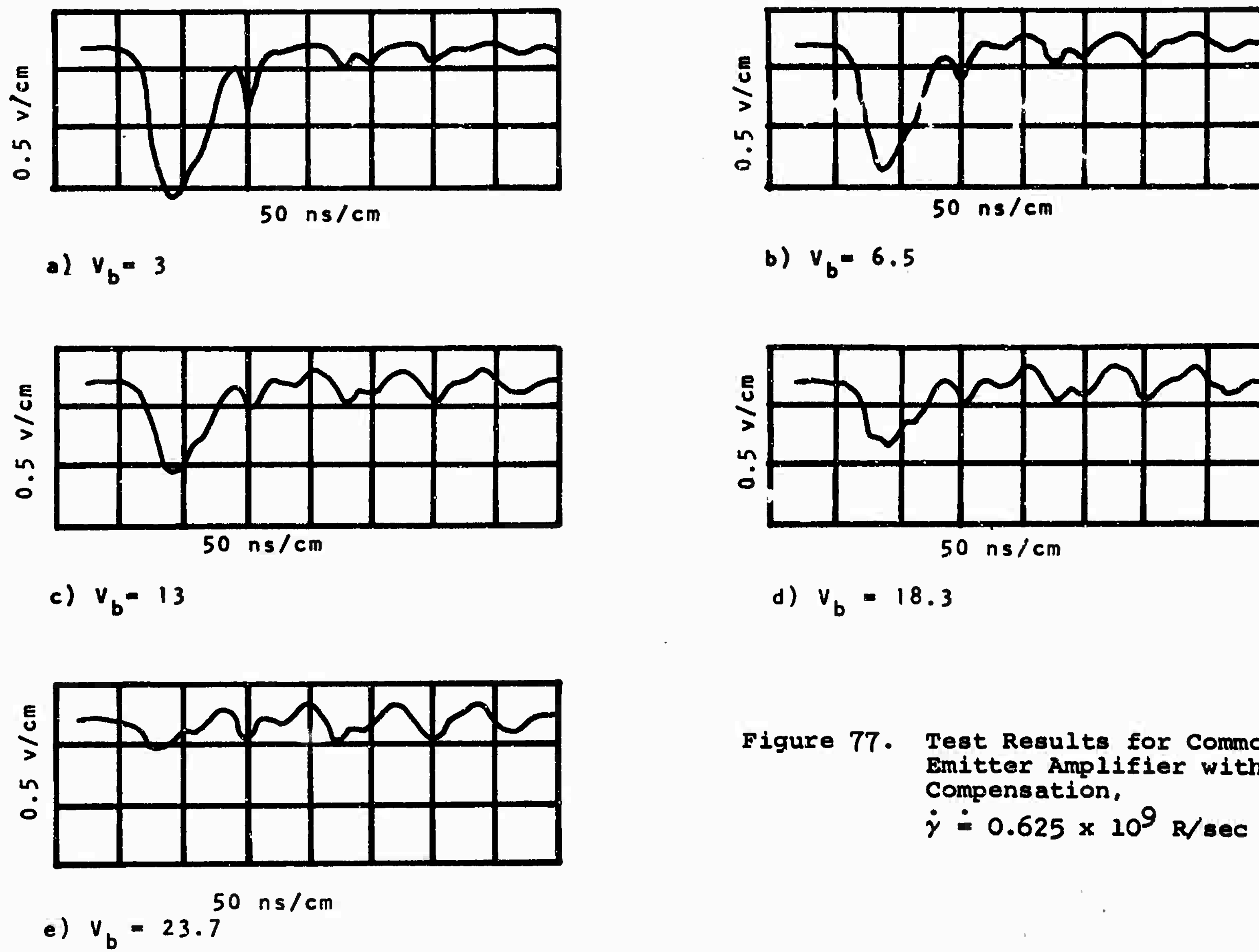


Figure 77. Test Results for Common-Emitter Amplifier with no Compensation, $\dot{\gamma} = 0.625 \times 10^9$ R/sec

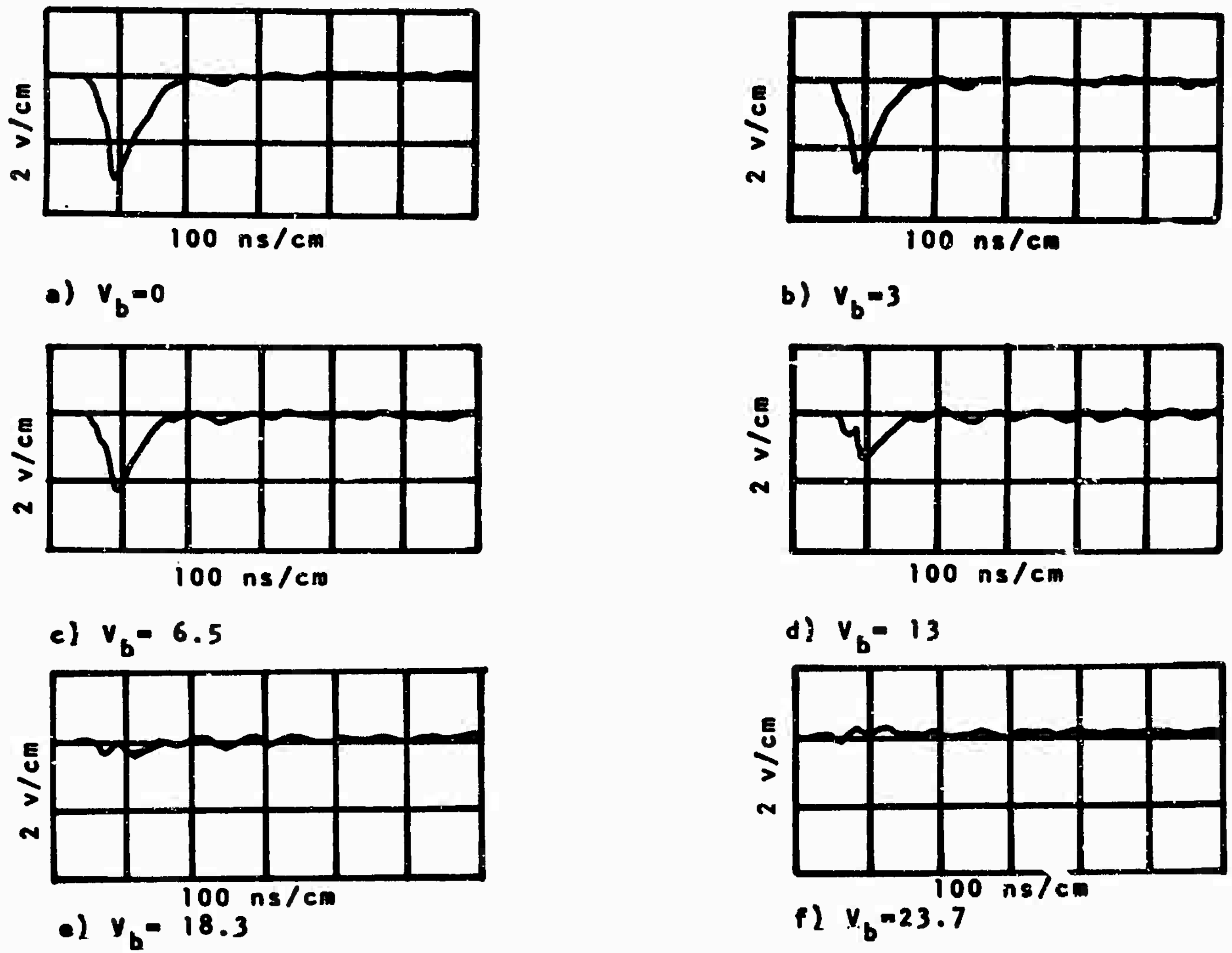


Figure 78. Test Results for Common-Emitter Amplifier with no Compensation, $\dot{\gamma} \doteq 2.75 \times 10^9$ R/sec

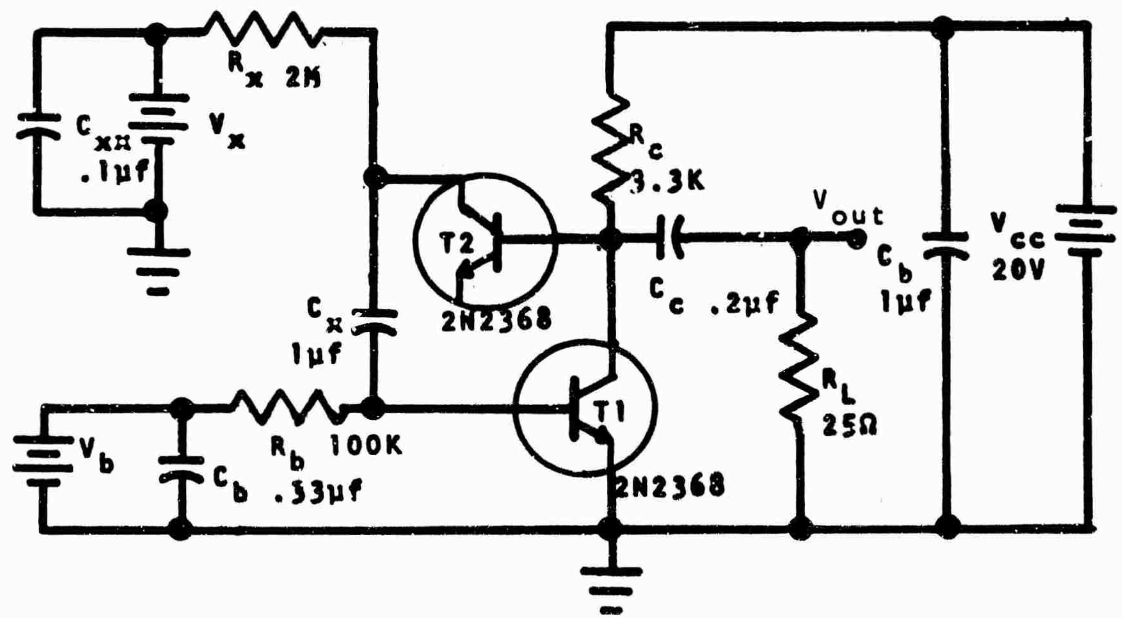


Figure 79. Common-Emitter Amplifier Test Circuit with Collector-to-Base Compensation

Figures 80 and 81 show the test results. Compare this with the CIRCUS results in figures 44 and 45. Also refer to the predicted results as given by equations (17), (20), and (22).

Base-to-Ground Compensation. Figure 82 shows the circuit tested. The resulting near-optimum compensation voltages, V_x, at each bias level are given on each of the output pulse drawings as shown in figures 83 and 84.

By reducing V_x, the positive part of the pulse can be reduced. The compensation is helpful in the active and near-cutoff regions of operation. For $V_b = 3$ volts, the ratios of the peak values are reduced by about 6 to 1 for $\dot{\gamma} \doteq 0.625 \times 10^9$ R/sec and by about 3 to 1 for $\dot{\gamma} \doteq 2.75 \times 10^9$ R/sec.

The maximum peak value of the output occurred at $V_b \doteq 1.5$ volts. The compensation was effective in the near-cutoff region (as indicated by equation (16)), but a negative component was still present as predicted by equation (25). In the active region, the output could be made positive or negative by varying V_x (equation (27) predicted this result).

The computer results (figures 47 and 48) were similar in shape to the experimental results (figures 83 and 84). For $\hat{I}_{pp} = \hat{I}_c$ the negative component predominates (this was observed experimentally also). Note that a small positive portion is also present in the experimental results.

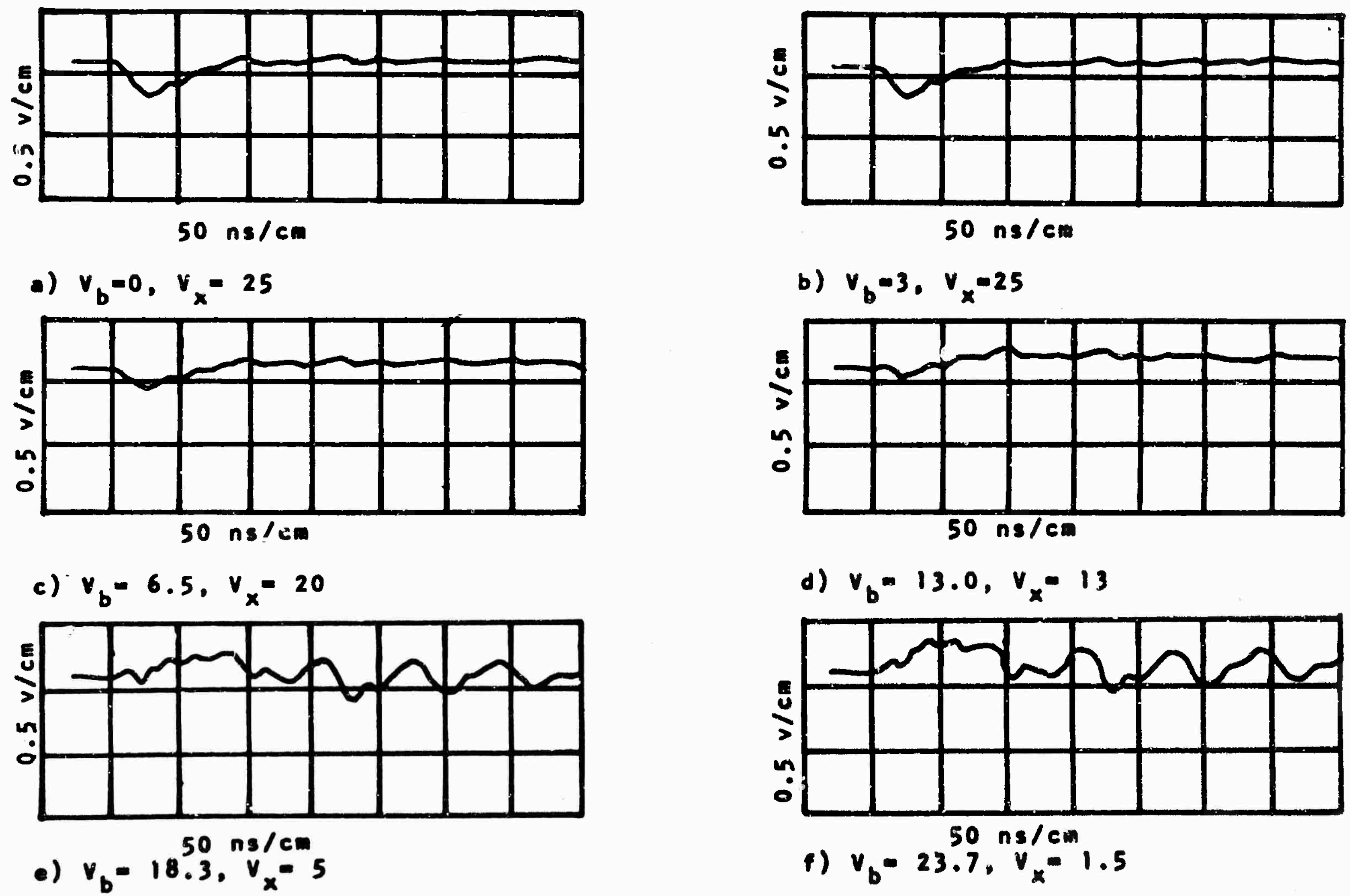


Figure 80. Test Results for Common-Emitter Amplifier with Collector-to-Base Compensation, $\dot{\gamma} \doteq 0.625 \times 10^9$ R/sec

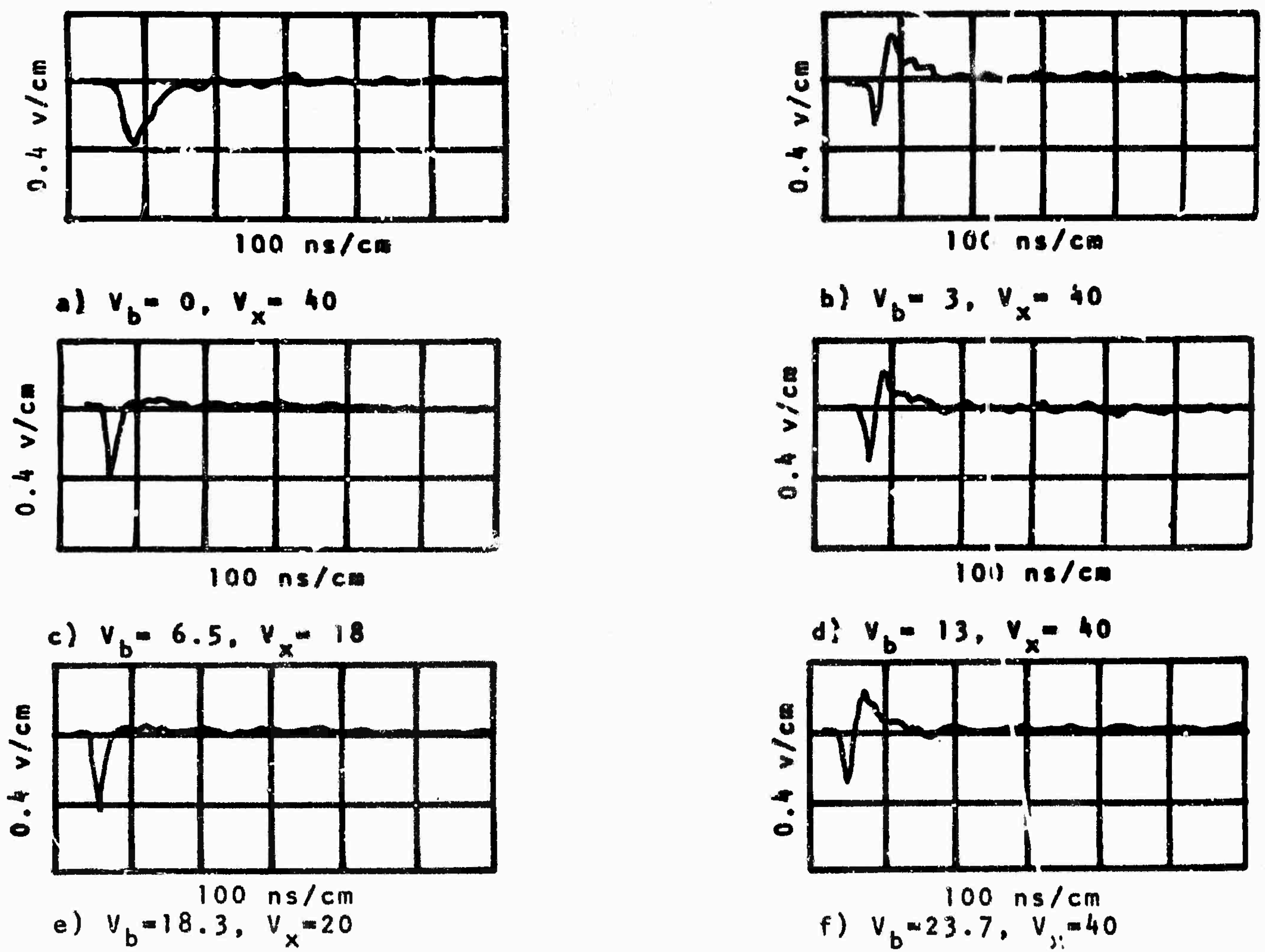


Figure 81. Test Results for Common-Emitter Amplifier with Collector-to-Base Compensation, $\dot{\gamma} \doteq 2.75 \times 10^9$ R/sec

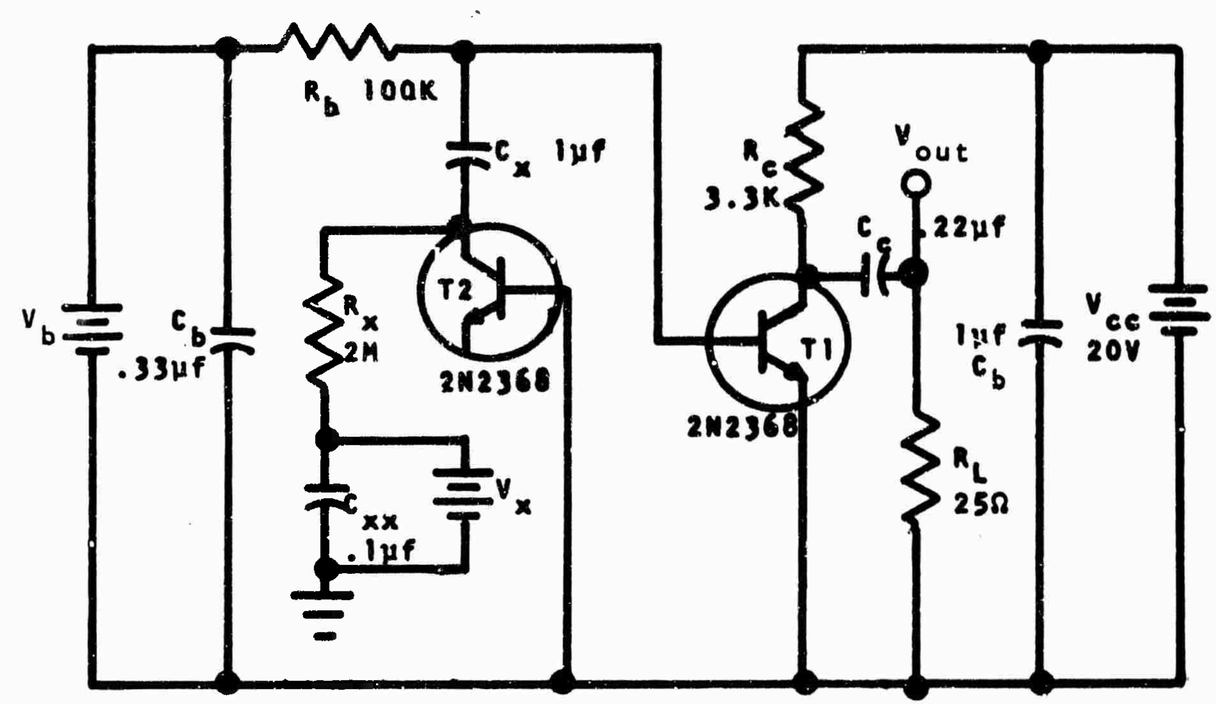


Figure 82. Common-Emitter Amplifier Test Circuit with Base-to-Ground Compensation

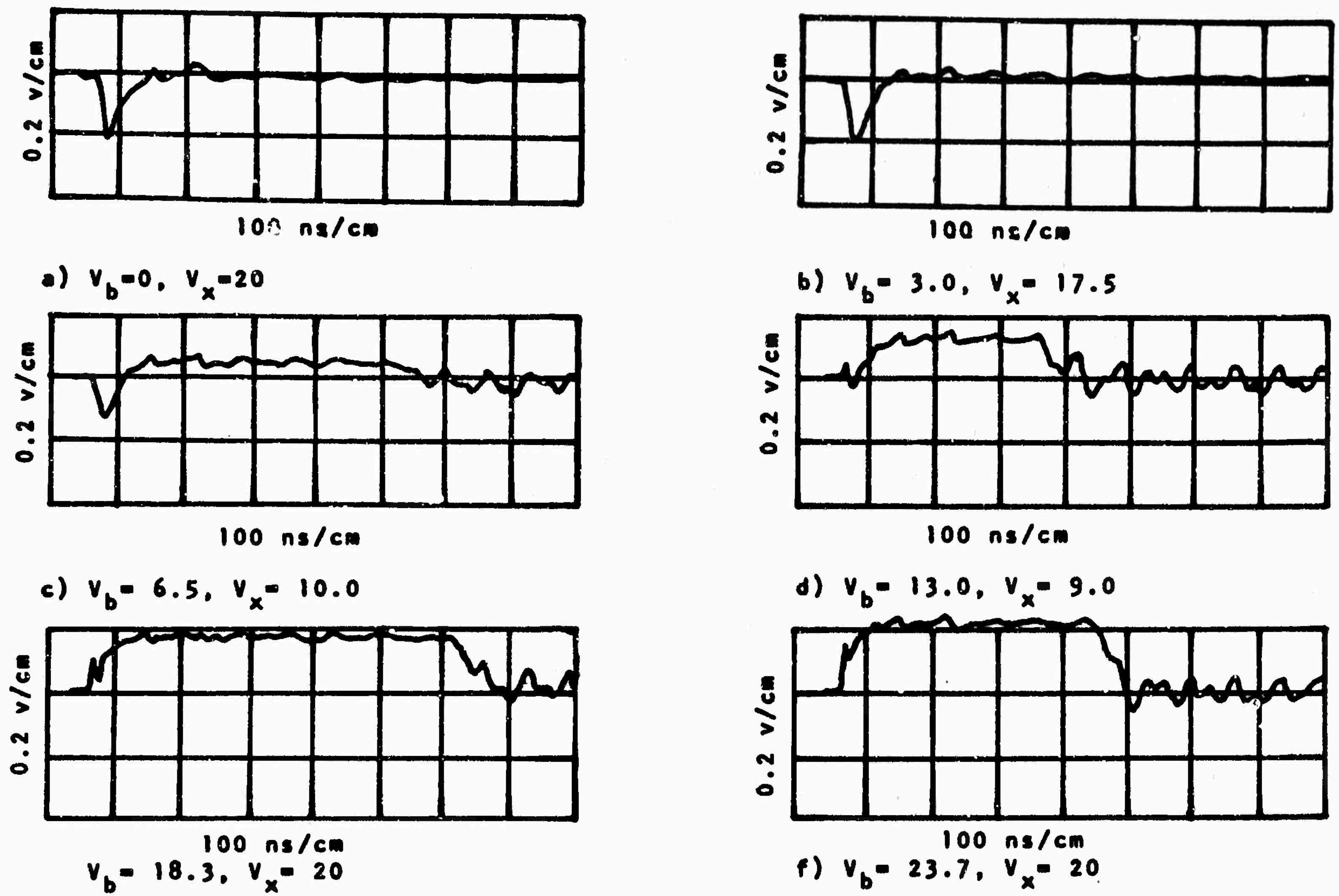


Figure 83. Test Results for Common-Emitter Amplifier with Base-to-Ground Compensation, $\dot{\gamma} \doteq 0.625 \times 10^9$ R/sec

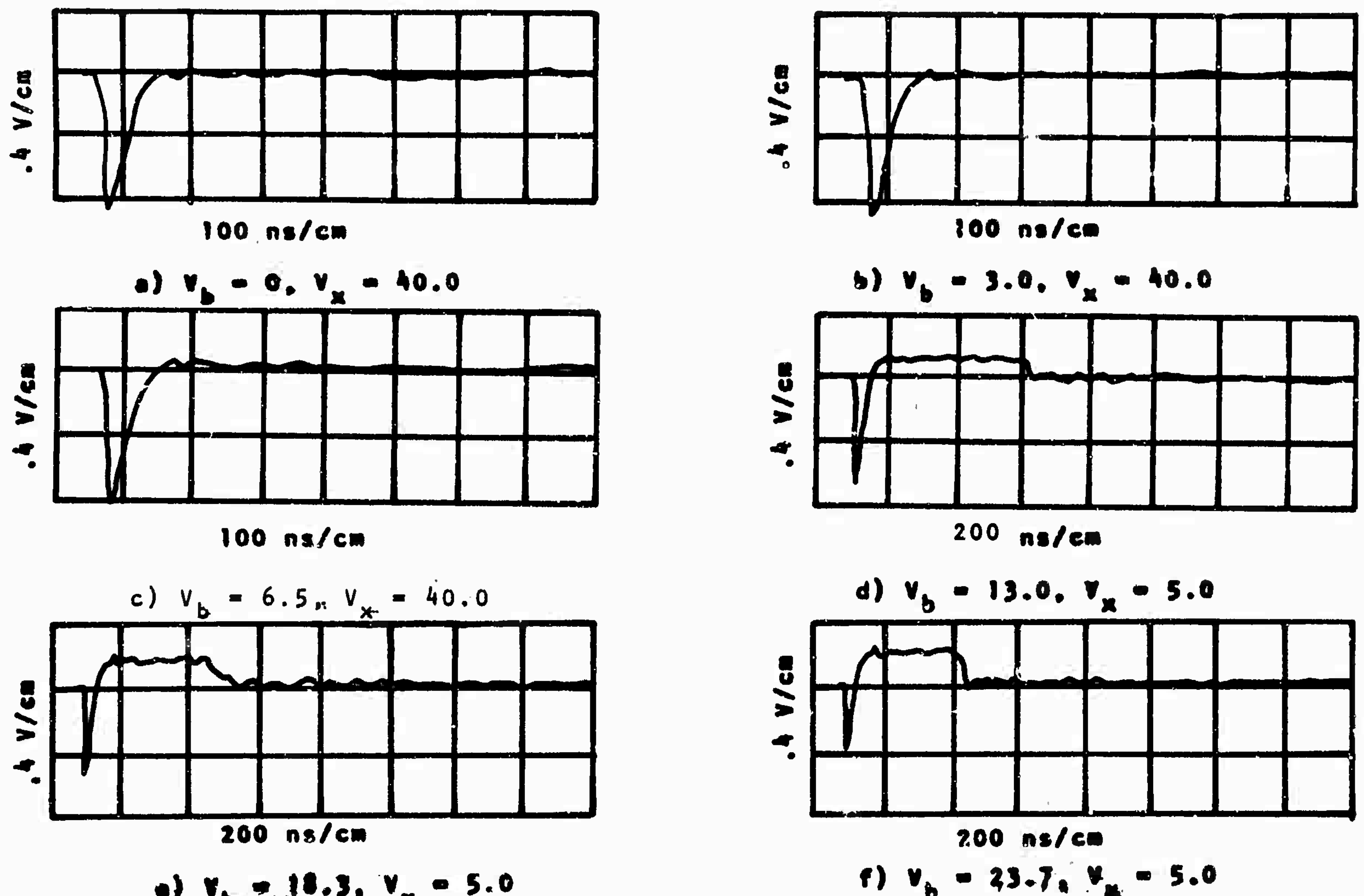


Figure 84. Test Results for Common-Emitter Amplifier with Base-to-Ground Compensation, $\dot{\gamma} \approx 2.75 \times 10^9$ R/sec

It was necessary to make V_x large for the positive portion to dominate.

The qualitative correlation of the predictions (equations 25 and 27) with the experimental data was adequate. In general base-to-ground compensation should be useful except in saturation operation; however, it does appear that collector-to-base compensation is more effective than base-to-ground compensation.

3. Common-Base Amplifier.

No Compensation. The test circuit for the common-base amplifier is given in figure 85. Figure 86 shows the test results. The load resistor, R_L, is a 50-ohm resistor paralleled by a properly terminated 50-ohm cable connected to a 517 oscilloscope.

The test results are shown for varying values of V_{eb} and two levels of radiation. The output pulses are negative and small, as predicted by equation (11). The transient collector current flowing is approximately I_{pp}.

Collector-to-Ground Compensation. Figure 87 shows the experimental test circuit used. The voltage V_x was varied to achieve near-optimum cancellation. The plots of the resulting output pulses are shown in figure 88. A comparison of figures 86 and 88 shows that at the lower level of radiation, the improvement was not great. At the higher radiation level, the improvement was about 3 to 1 in the

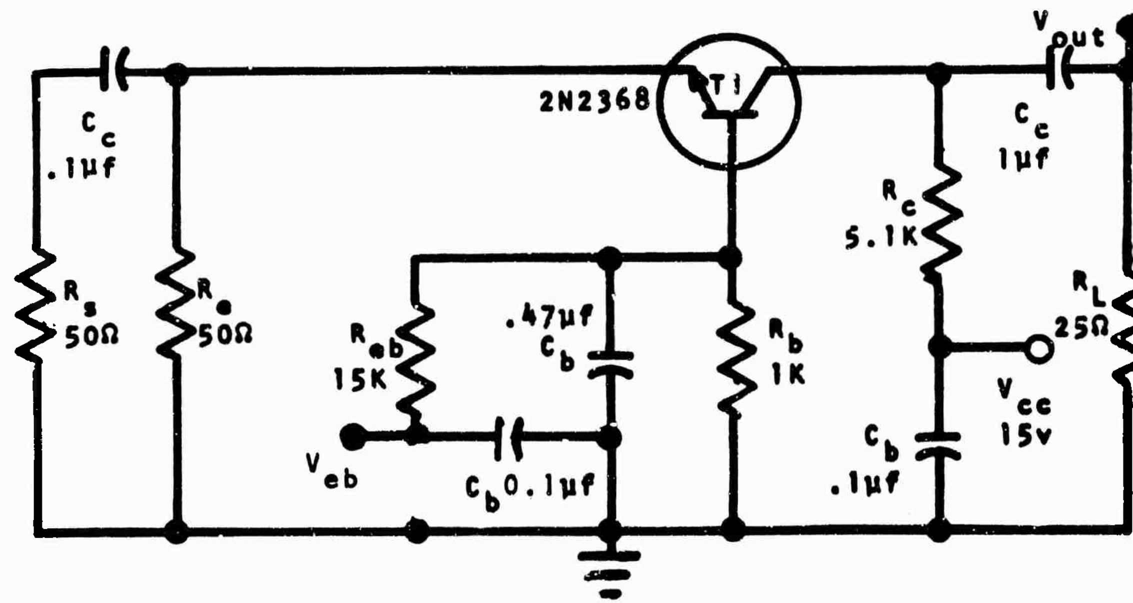


Figure 85. Test Circuit for Common-Base Amplifier with no Compensation

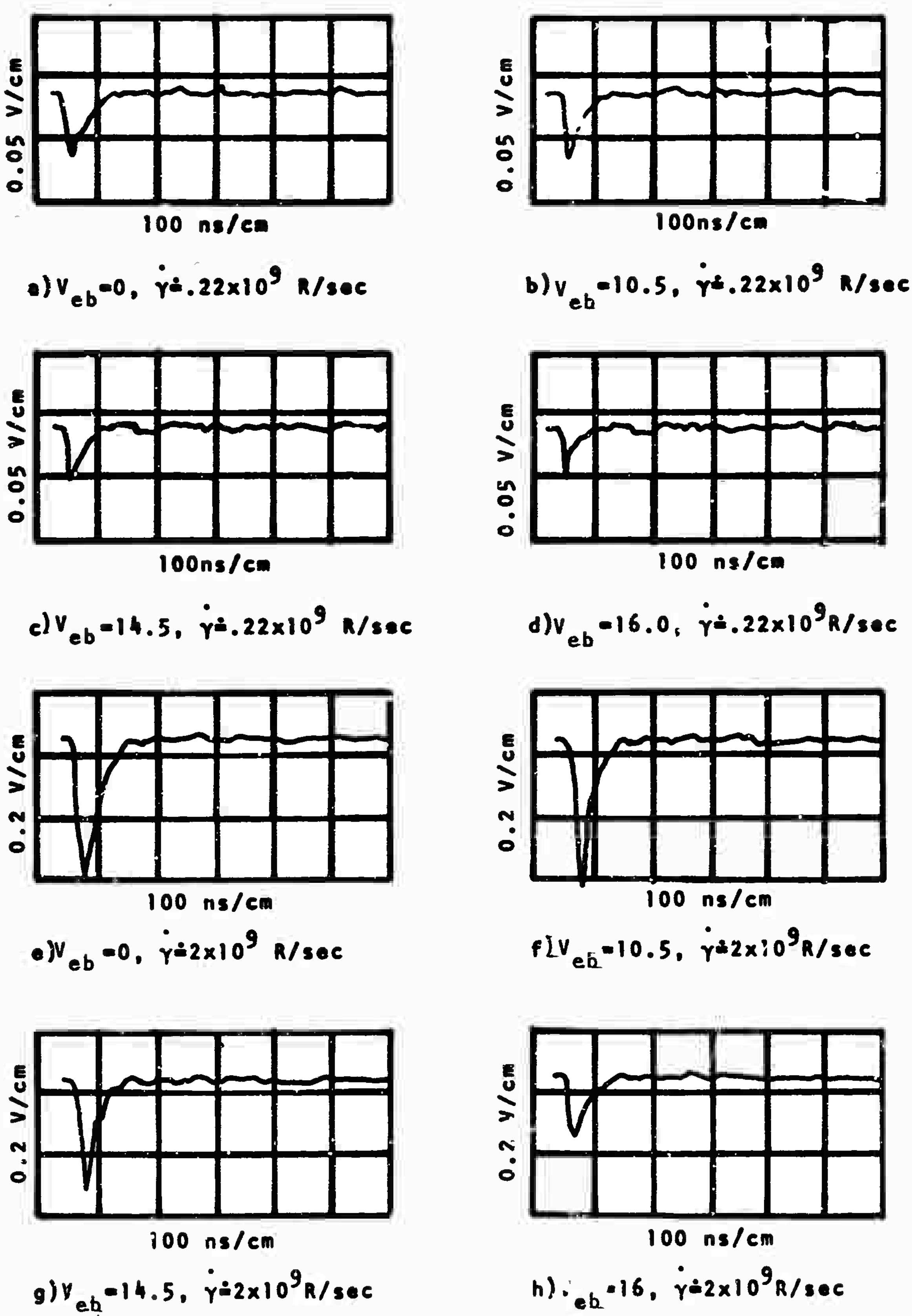


Figure 86. Test Results for Common-Base Amplifier with no Compensation

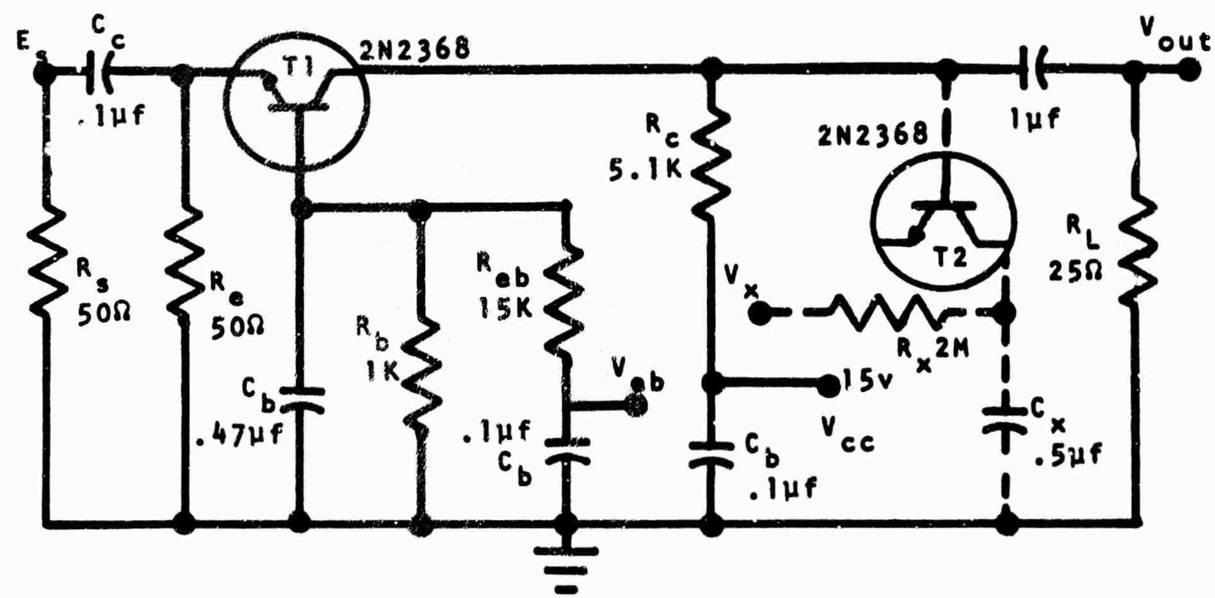
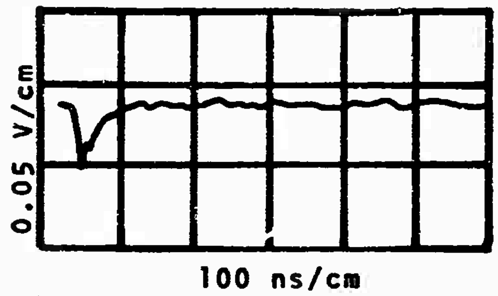
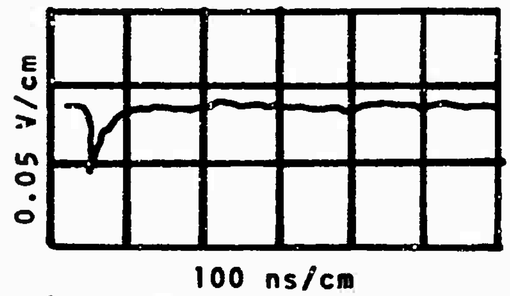


Figure 87. Test Circuit for Common-Base Amplifier with Collector-to-Ground Compensation

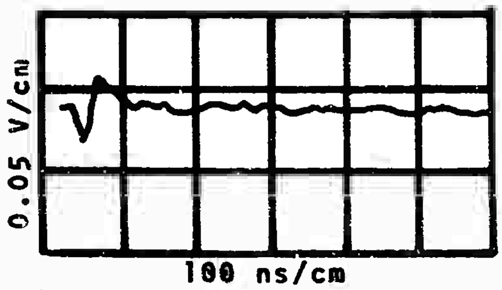


a) $V_{eb}=0$, $V_x=39$

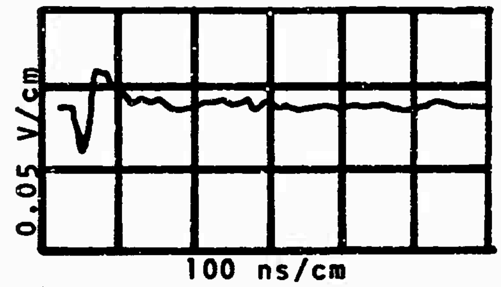


b) $V_{eb}=10.5$, $V_x=39$

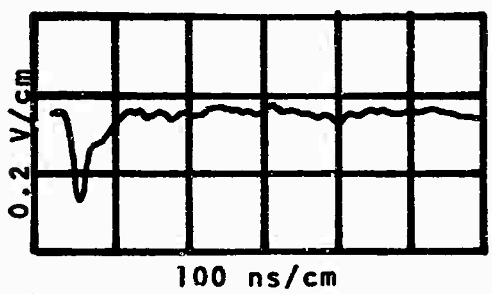
For a), b), c), and d), $\dot{\gamma} \doteq 0.22 \times 10^9$ R/sec



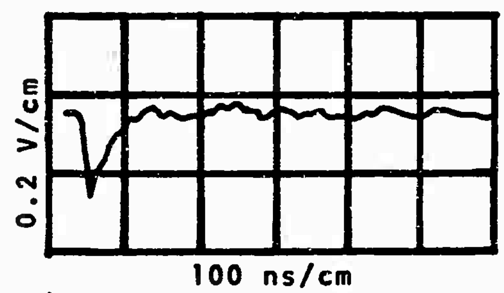
c) $V_{eb}=14.5$, $V_x=39$



d) $V_{eb}=16$, $V_x=39$

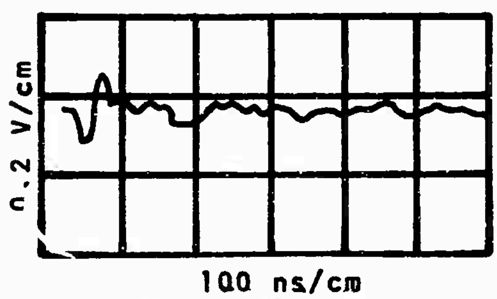


e) $V_{eb}=0$, $V_x=39$

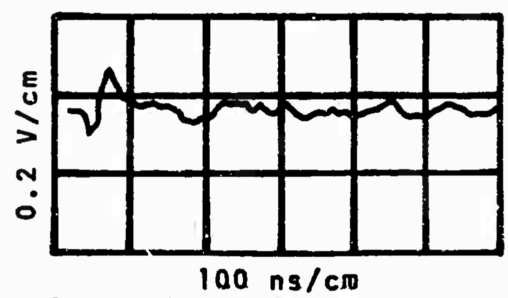


f) $V_{eb}=10.5$, $V_x=39$

For e), f), g) and h), $\dot{\gamma} \doteq 2.0 \times 10^9$ R/sec



g) $V_{eb}=14.5$, $V_x=39$



h) $V_{eb}=16$, $V_x=39$

Figure 88. Test Results for Common-Base Amplifier with Collector-to-Ground Compensation

cutoff and active regions, with essentially no improvement in the saturation region. As predicted by equation (46), $\hat{I}_c$ had to be greater than $\hat{I}_{pp}$ for the best cancellation. Equation (47) predicts that the output would be quite small in the saturation region. If V_{eb} had been larger, the output would have been reduced further. The computer results were similar (figures 53 and 54) in shape to the experimental results when V_x was too small for best compensation (i.e., $\hat{I}_c \doteq \hat{I}_{pp}$).

In summary, this compensation technique may be applied for any region of operation; however, the reduction in transient response is modest.

<u>Output-to-Ground Compensation</u>. This method and the preceding one should be the same. Computer calculations and experimental tests were made to ensure that this was correct. The results were identical for these two compensation methods and no additional comments are required. The test circuit is shown in figure 89, and the test results are shown in figure 90.

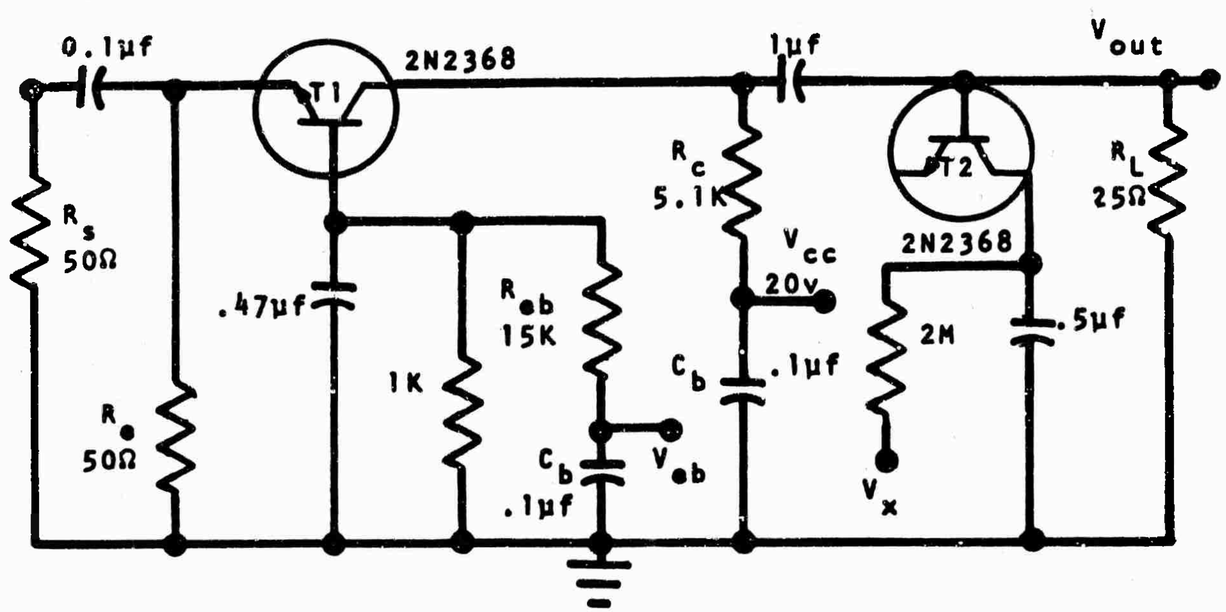
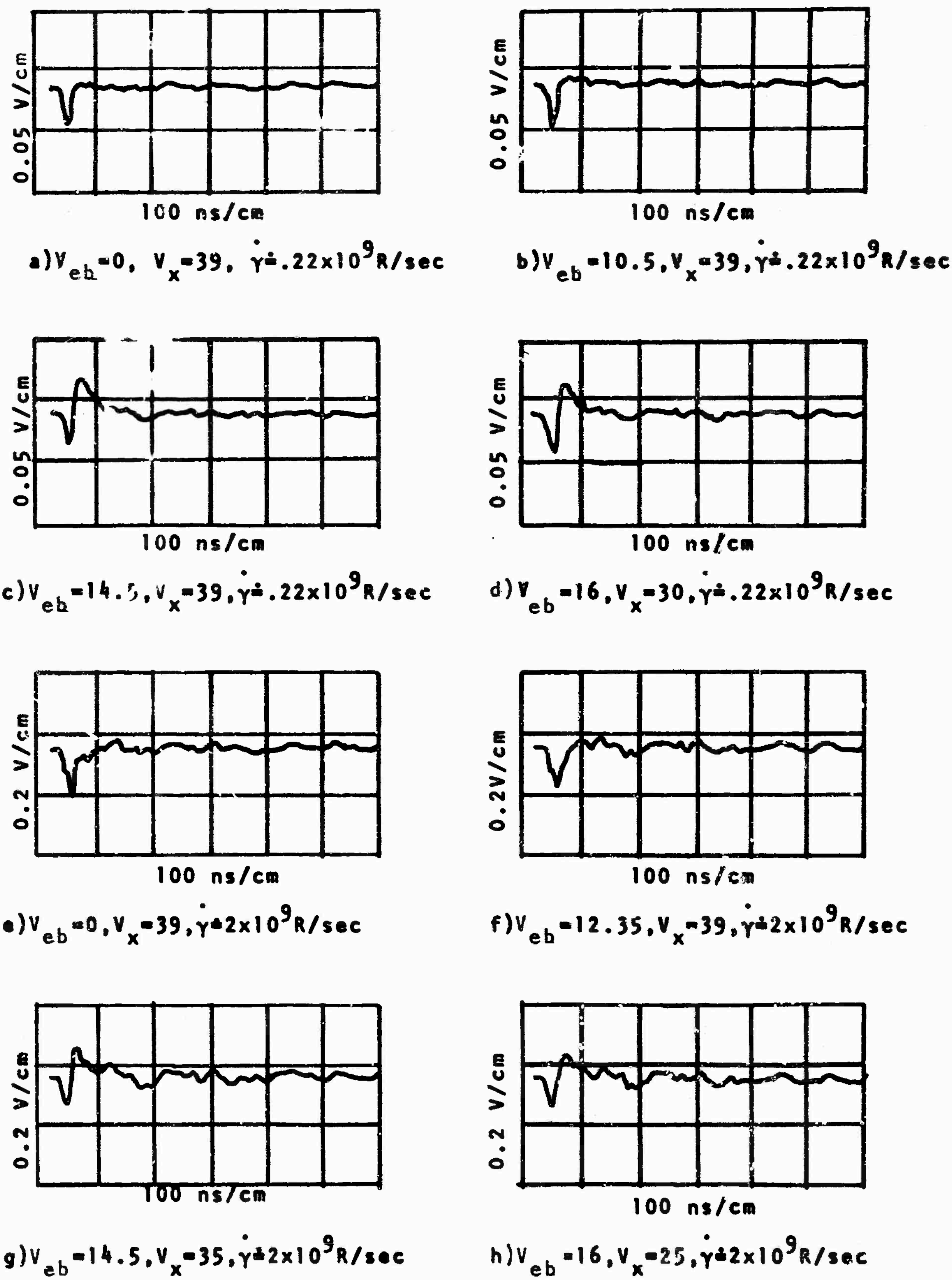


Figure 89. Test Circuit for Common-Base Amplifier with Output-to-Ground Compensation



a) $V_{eb}=0$, $V_x=39$, $\dot{\gamma}\doteq .22\times10^9$ R/sec

b) $V_{eb}=10.5$, $V_x=39$, $\dot{\gamma}\doteq .22\times10^9$ R/sec

c) $V_{eb}=14.5$, $V_x=39$, $\dot{\gamma}\doteq .22\times10^9$ R/sec

d) $V_{eb}=16$, $V_x=30$, $\dot{\gamma}\doteq .22\times10^9$ R/sec

e) $V_{eb}=0$, $V_x=39$, $\dot{\gamma}\doteq 2\times10^9$ R/sec

f) $V_{eb}=12.35$, $V_x=39$, $\dot{\gamma}\doteq 2\times10^9$ R/sec

g) $V_{eb}=14.5$, $V_x=35$, $\dot{\gamma}\doteq 2\times10^9$ R/sec

h) $V_{eb}=16$, $V_x=25$, $\dot{\gamma}\doteq 2\times10^9$ R/sec

Figure 90. Test Results for Common-Base Amplifier with Output-to-Ground Compensation

4. <u>Common-Collector Amplifier</u>

<u>No Compensation</u>. The test circuit for the common-collector amplifier is shown in figure 91. Once again the load resistance is 50Ω in parallel with a properly terminated 50Ω cable connected to a 517 oscilloscope. Figure 92 shows the test results which correspond almost exactly to those predicted by equations (67), (68), and (70) for no compensation ($\hat{I}_c = 0$). The computer predictions (figure 56) are not in close agreement with the experimental data. The output did not decrease as saturation was approached and the output was too high for $V_b = 0$.

<u>Collector-to-Base Compensation</u>. The test circuit is shown in figure 93 and the test results in figure 94. This compensation technique is equivalent (for the common-collector amplifier) to the base-to-ground compensation circuit as shown in figure 95. The computed and experimental results were essentially the same for both compensation methods. The following comments apply to both circuits. In cutoff, the pulse output is small, in agreement with the prediction of equation (67). For the active region of operation, the pulse is made either positive or negative by adjusting V_x (as predicted by equation (68)). The experimental results agree with that predicted by equation (69). Further reduction of V_x should have made the positive pulse smaller; this would make the results agree with equations (68) and (69). The computer results (figures 59 and 60) agree poorly with the experimental results.

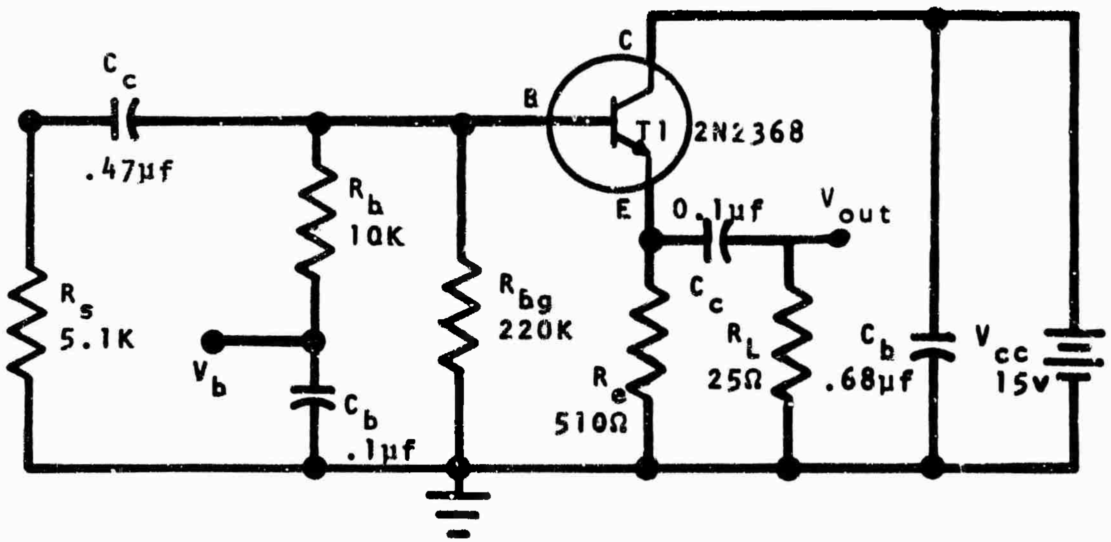


Figure 91. Test Circuit for Common-Collector Amplifier with no Compensation

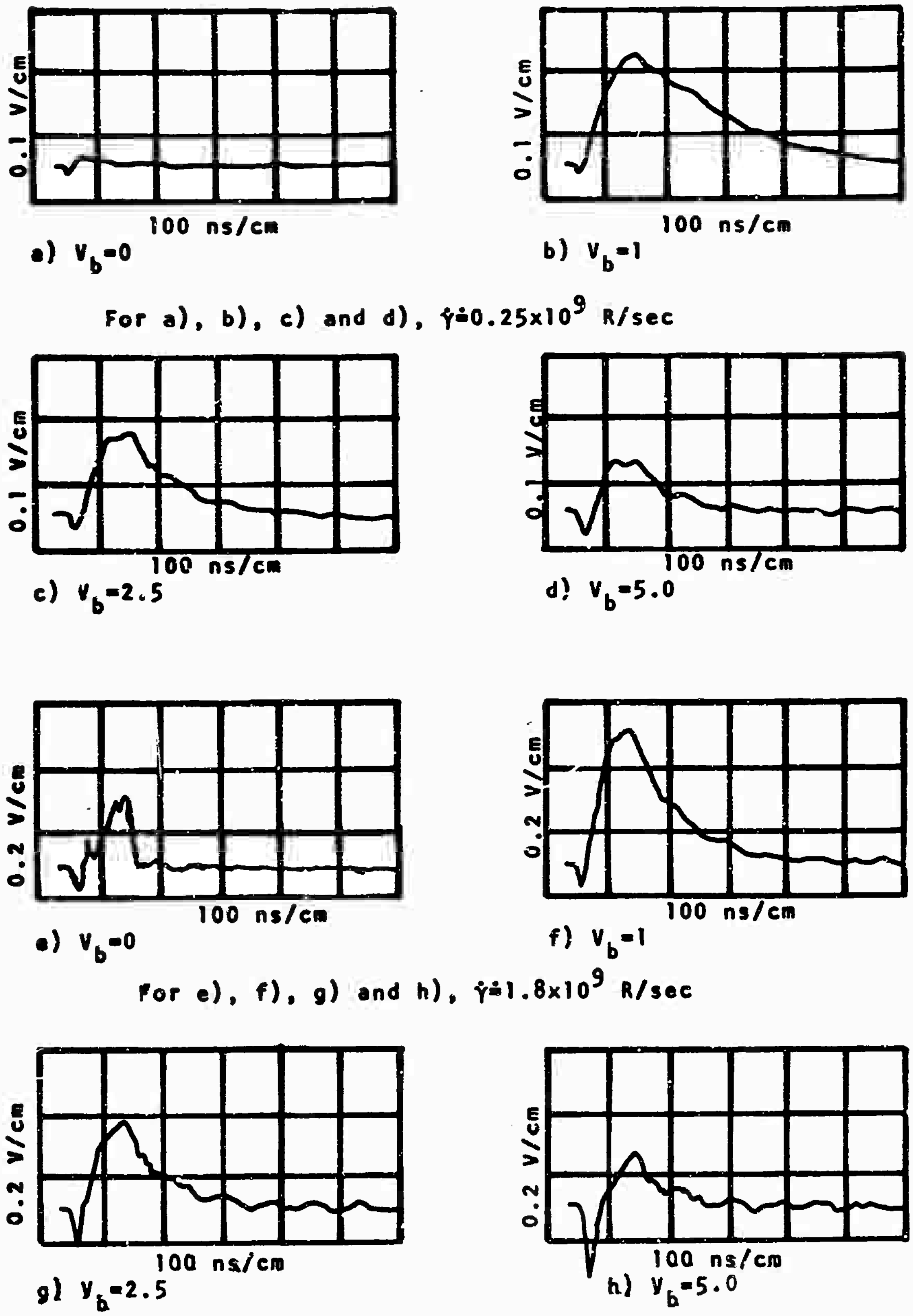


Figure 92. Test Results for Common-Collector Amplifier with no Compensation

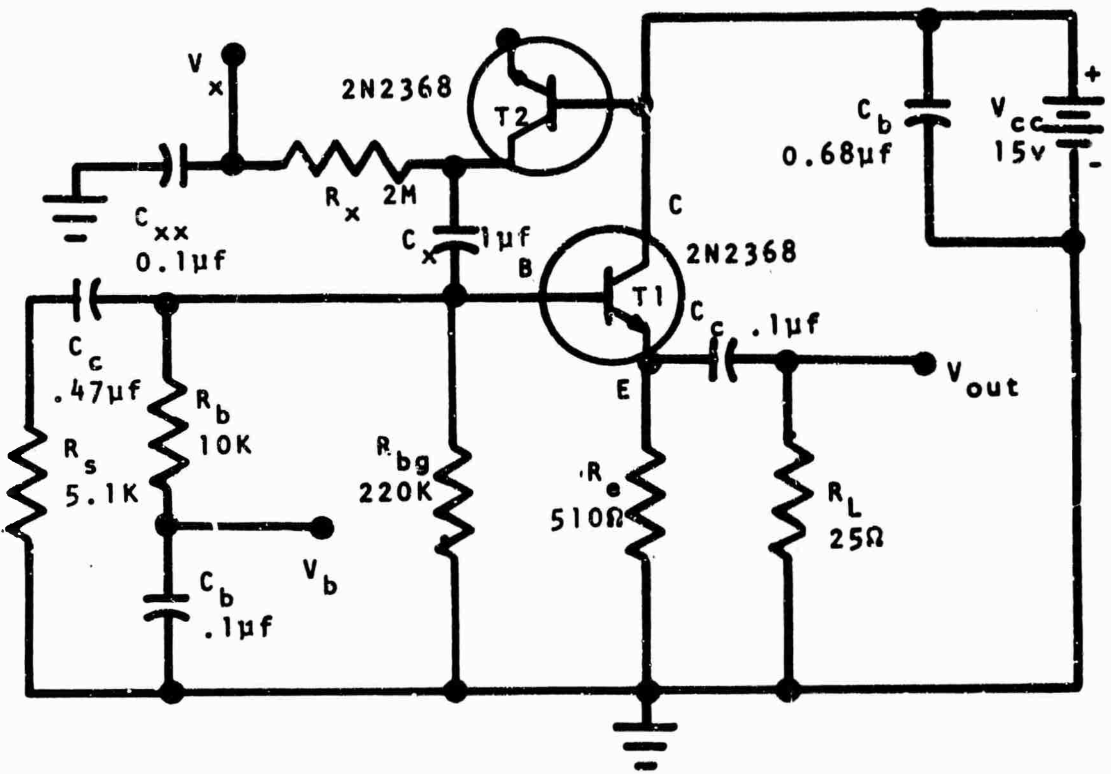


Figure 93. Test Circuit for Common-Collector Amplifier with Collector-to-Base Compensation

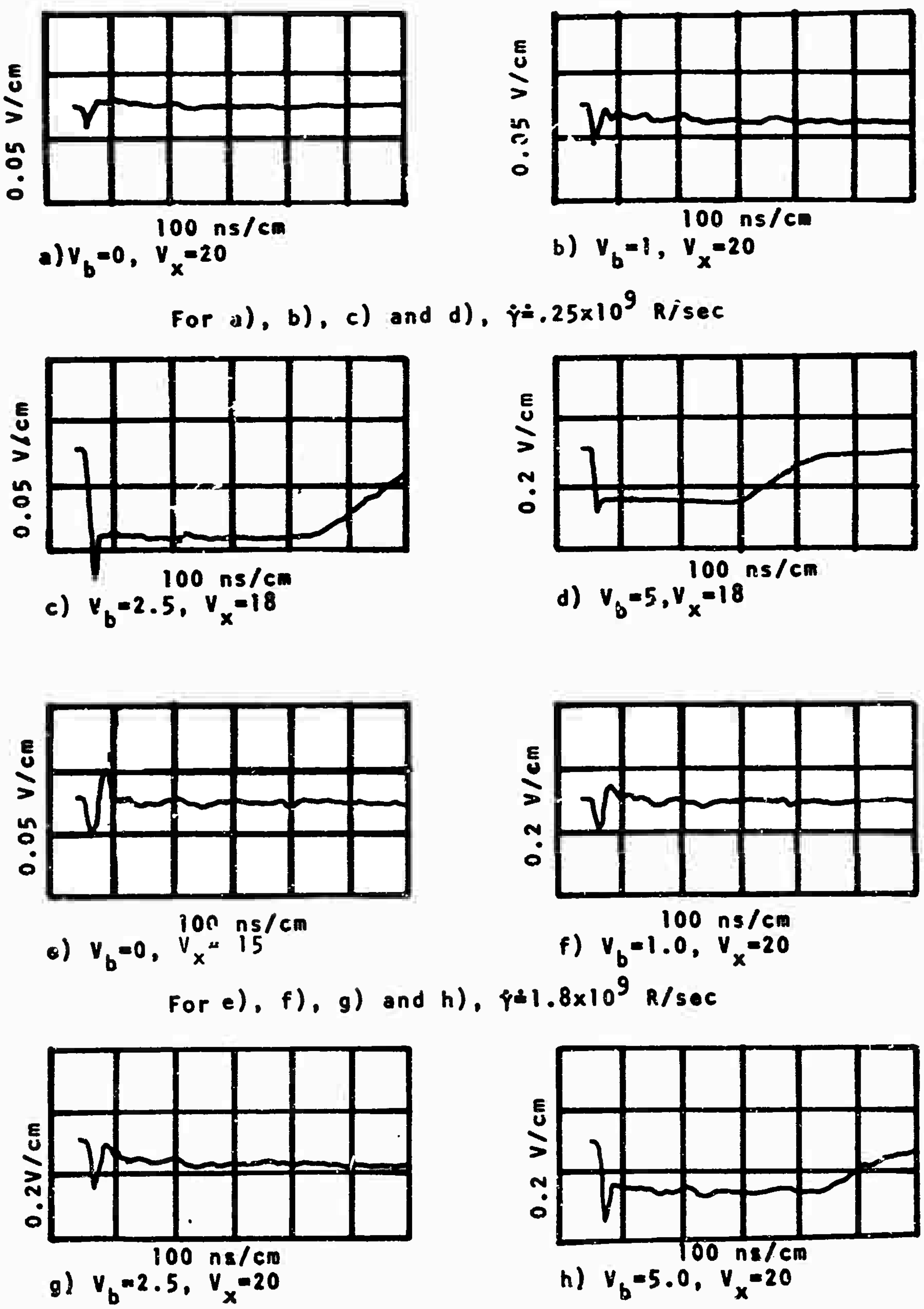


Figure 94. Test Results for Common-Collector Amplifier with Collector-to-Base Compensation

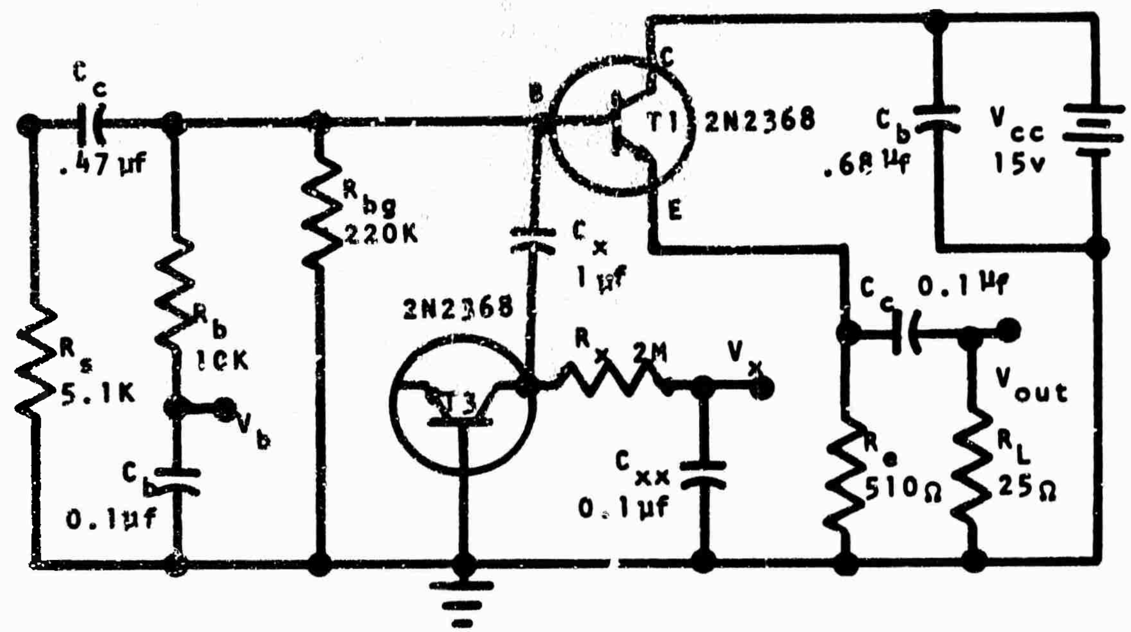


Figure 95. Test Circuit for Common-Collector Amplifier with Base-to-Ground Compensation

Base-to-Ground Compensation. The test circuit is shown in figure 95, and the experimental results are shown in figure 96. The discussion of this circuit is given in the preceding section.

5. *Common-Base to Common-Collector Amplifier*

The test circuit for the common-base amplifier driving a common-collector amplifier is shown in figure 97. Once again the load resistance is 50Ω in parallel with a properly terminated 50Ω cable connected to a 517 oscilloscope. The test results are shown for two radiation levels in figures 98 through 101. The data are presented for fixed values of V_{eb} with V_b equal to 0, 1, or 2.5 volts. The results for $V_b = 5$ are not shown because the output became low for the common-collector amplifier saturated (as predicted by equations (95), (100), and (104)). Note that the amplifier outputs are negative whereas the normal output of a common collector during irradiation is positive. This indicates that $\hat{I}_{pp1}$ was too large. In an attempt to make $\hat{I}_{pp2}$ larger than $\hat{I}_{pp1}$ and thus achieve better compensation, transistor T2 was pushed about one inch closer to the source than T1. This resulted in considerable improvement and is the reason for the two radiation levels ($\dot{\gamma}_1$ for T_1 and $\dot{\gamma}_2$ for T_2) indicated for each test. Further improvements in the inherent compensation should be obtained by making $\hat{I}_{pp2}$ even larger. This is as

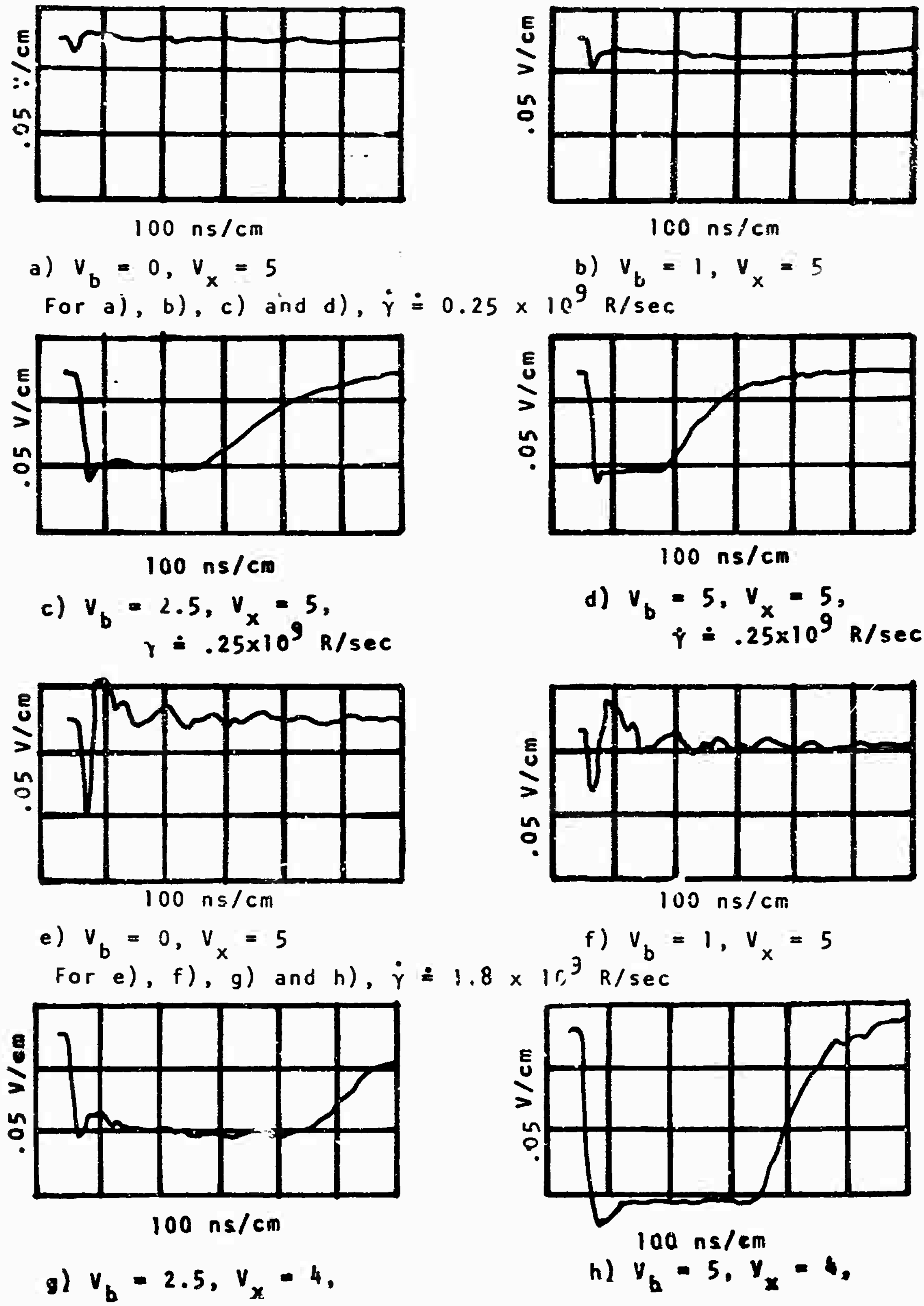


Figure 96. Test Results for Common-Collector Amplifier with Base-to-Ground Compensation

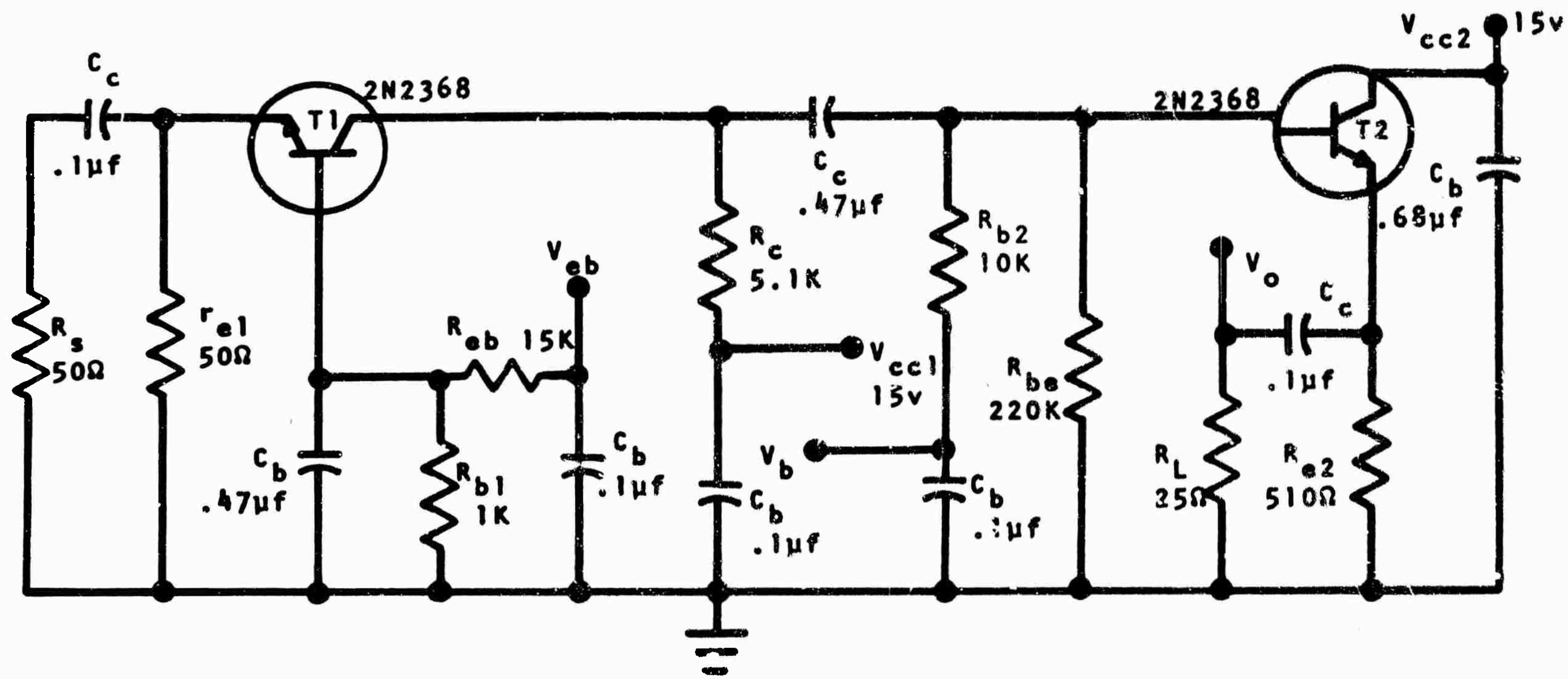
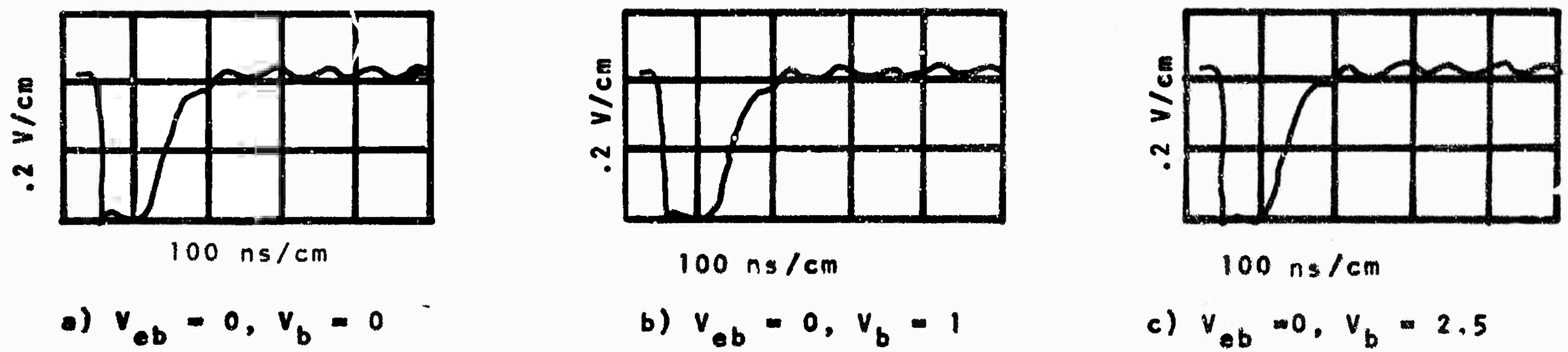
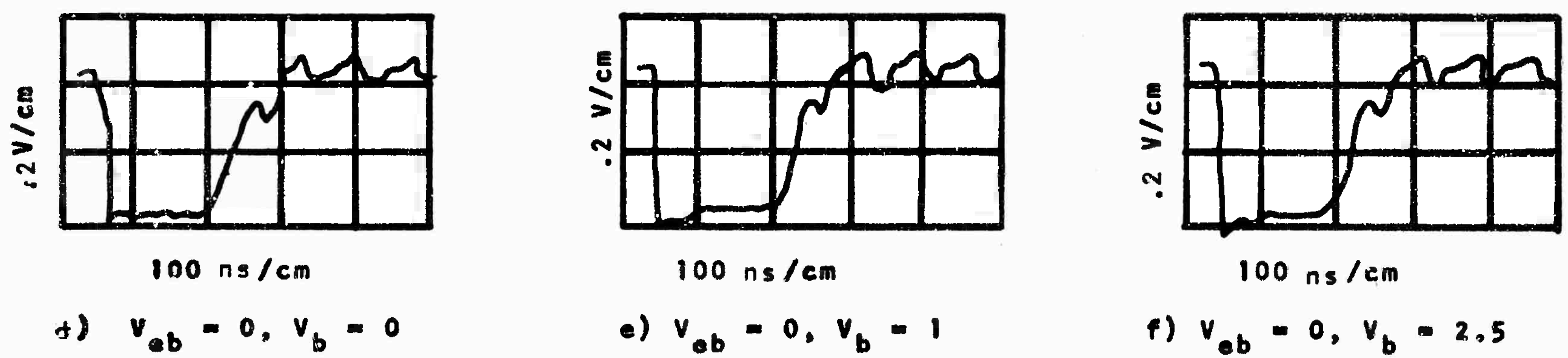


Figure 97. Test Circuit for Common-Base to Common-Collector Amplifier

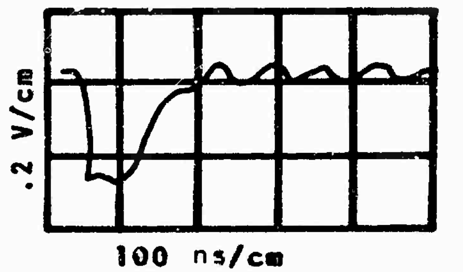


For a), b), and c): $\dot{\gamma}_1 \doteq .225 \times 10^9$ R/sec and $\dot{\gamma}_2 \doteq .31 \times 10^9$ R/sec

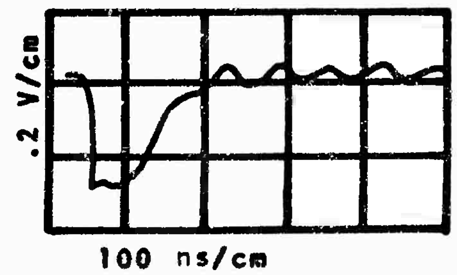


For d), e), and f): $\dot{\gamma} \doteq 1.5 \times 10^9$ R/sec and $\dot{\gamma}_2 \doteq 2 \times 10^9$ R/sec

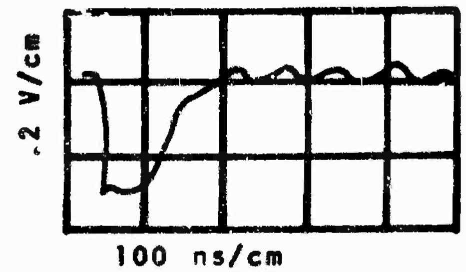
Figure 98. Test Results for Common-Base to Common-Collector Amplifier, $V_{eb} = 0$



a) $V_{eb} = 12.35$, $V_b = 0$

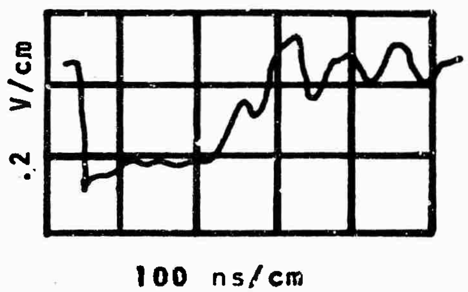


b) $V_{eb} = 12.35$, $V_b = 1$

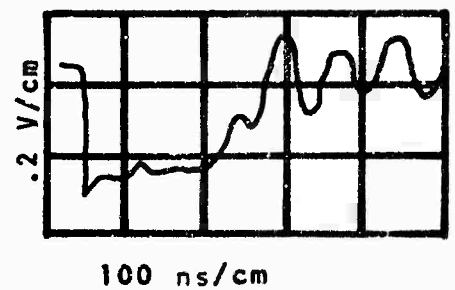


c) $V_{eb} = 12.35$, $V_b = 2.5$

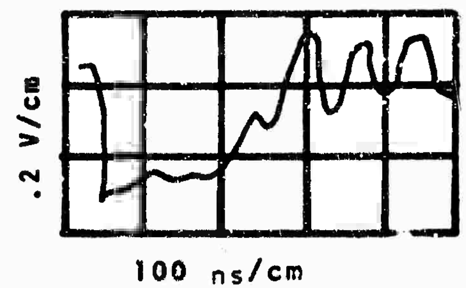
For a), b), and c): $\dot{\gamma}_1 \doteq .225 \times 10^9$ R/sec and $\dot{\gamma}_2 = .31 \times 10^9$ R/sec



d) $V_{eb} = 12.35$, $V_b = 0$



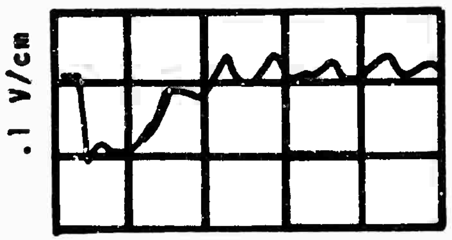
e) $V_{eb} = 12.35$, $V_b = 1$



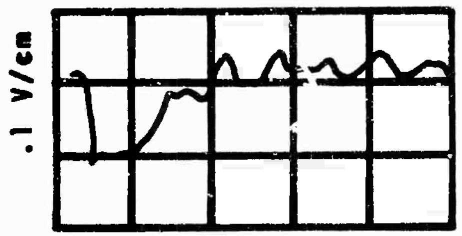
f) $V_{eb} = 12.35$, $V_b = 2.5$

For d), e), and f): $\dot{\gamma}_1 \doteq 1.5 \times 10^9$ R/sec and $\dot{\gamma}_2 \doteq 2 \times 10^9$ R/sec

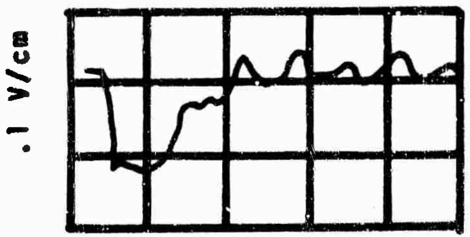
Figure 99. Test Results for Common-Base to Common-Collector Amplifier, $V_{cb} = 12.35$



a) $V_{eb} = 14.5$, $V_b = 0$

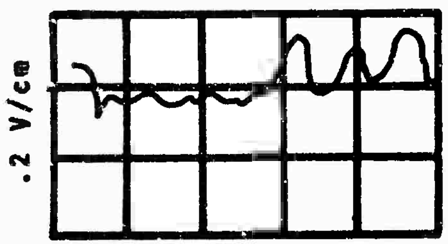


b) $V_{eb} = 14.5$, $V_b = 1$

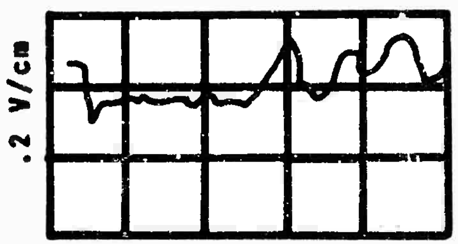


c) $V_{eb} = 14.5$, $V_b = 2.5$

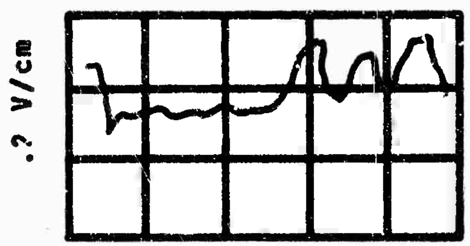
For a), b), and c): $\gamma_1 \doteq .225 \times 10^9$ R/sec and $\gamma_2 \doteq .31 \times 10^9$ R/sec



d) $V_{eb} = 14.5$, $V_b = 0$



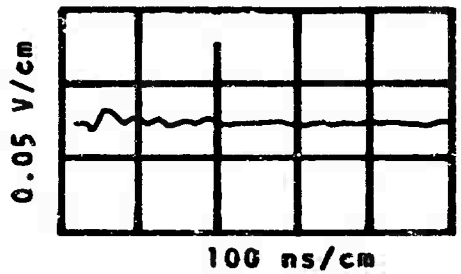
e) $V_{eb} = 14.5$, $V_b = 1$



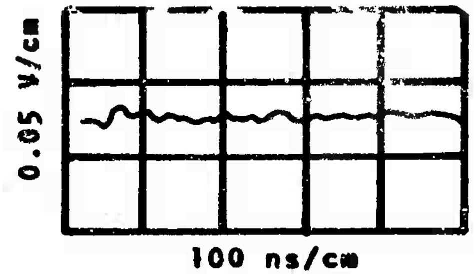
f) $V_{eb} = 14.5$, $V_b = 2.5$

For d), e), and f): $\gamma_1 \doteq 1.5 \times 10^9$ R/sec and $\gamma_2 \doteq 2 \times 10^9$ R/sec

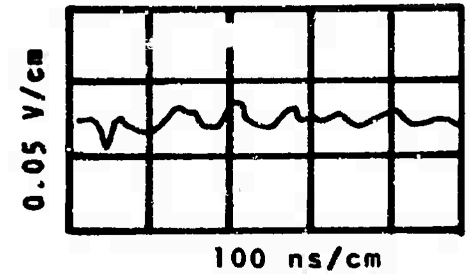
Figure 100. Test Results for Common-Base to Common-Collector Amplifier, $V_{eb} = 14.5$



a) $V_{eb}=16$, $V_b=0$

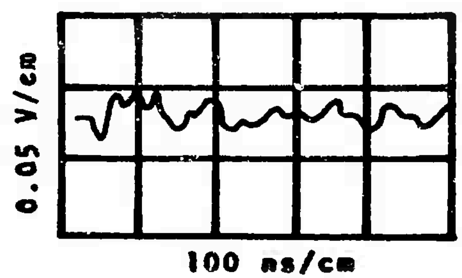


b) $V_{eb}=16$, $V_b=1$

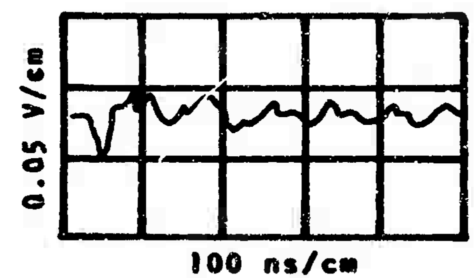


c) $V_{eb}=16$, $V_b=2.5$

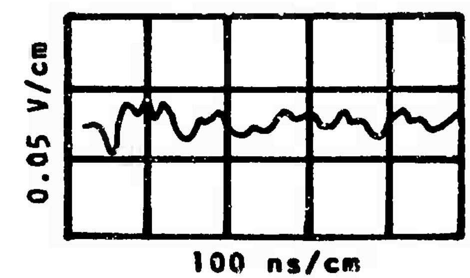
For a), b) and c), $\dot{\gamma}_1 \doteq 0.225\times10^9$ R/sec and $\dot{\gamma}_2 \doteq 0.31\times10^9$ R/sec



d) $V_{eb}=16$, $V_b=0$



e) $V_{eb}=16$, $V_b=1$



f) $V_{eb}=16$, $V_b=2.5$

For d), e) and f), $\dot{\gamma}_1 \doteq 1.5\times10^9$ R/sec and $\dot{\gamma}_2 \doteq 2.0\times10^9$ R/sec

Figure 101. Test Results for Common-Base to Common-Collector Amplifier, $V_{eb} = 16$

predicted by equations (94), (96), (99), and (101). Another indication of the correctness of this result is that the compensation improved as the common-base amplifier was driven further toward saturation. By careful design or by selection of the junctions in T1 and T2, the required relationship between $\hat{I}_{pp1}$ and $\hat{I}_{pp2}$ that will result in a low transient output for any particular mode of operation should be obtainable. The computer results in figures 65 through 74 are similar in shape to the experimental results. These computations showed the output becoming positive as the common-base amplifier went further into saturation. This agrees with the predictions previously discussed.

6. Three-Transistor ac-Coupled Video Amplifier

The test circuit for a three-transistor, ac-coupled video amplifier is shown in figure 102. For the first two stages of this amplifier, the low-level video amplifier PSC-18 listed in the preferred circuit handbook for the Bureau of Naval Weapons (reference 19) was used. The third stage is an intermediate-level video amplifier which is the first half of PSC-19 (reference 19). Complete descriptions of the characteristics of the amplifiers are given in this reference.

Compensation junctions T4, T5, and T6 were added from the collector-to-base junction of the active transistor to reduce the transient-radiation response. The amplifier worked

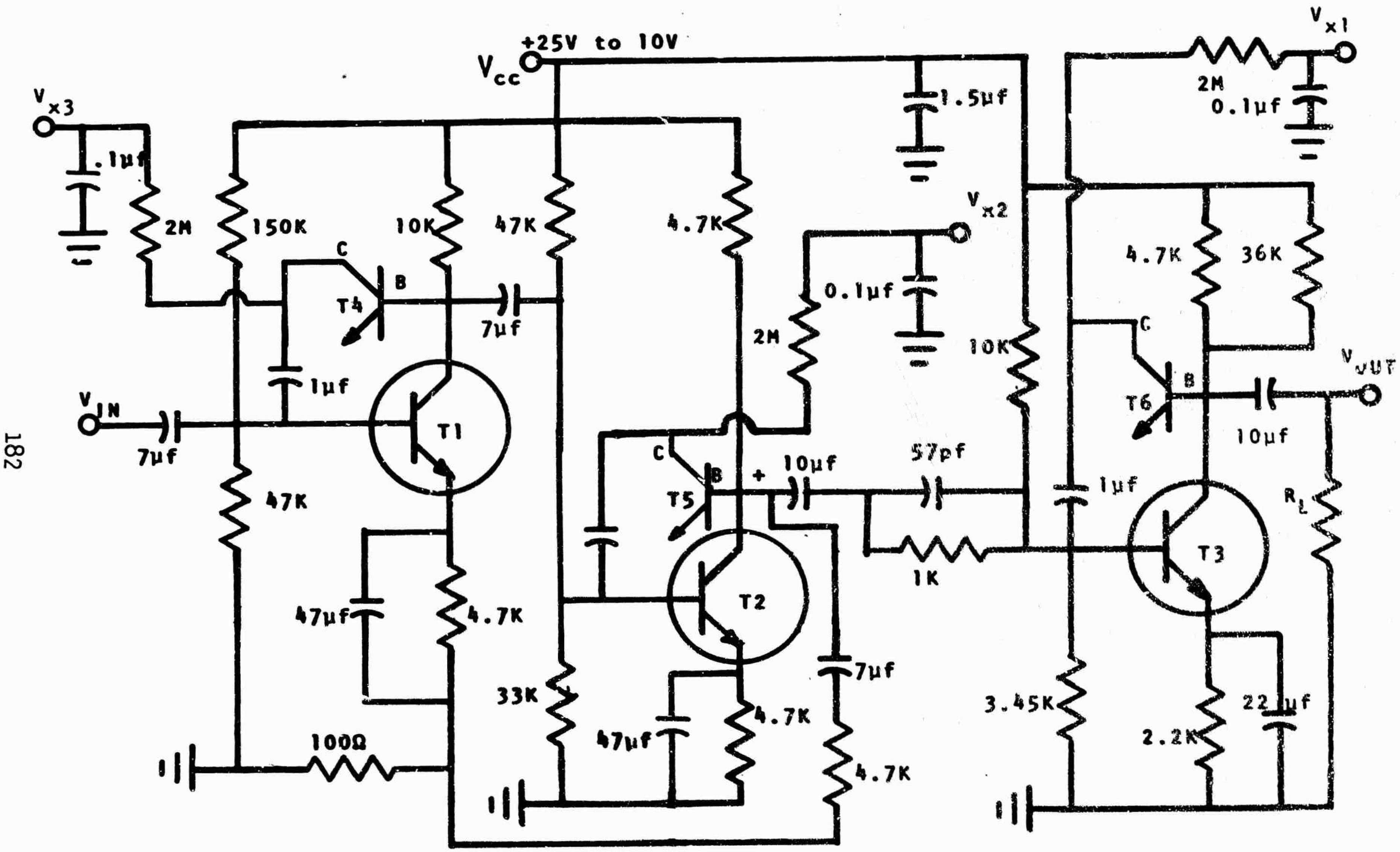


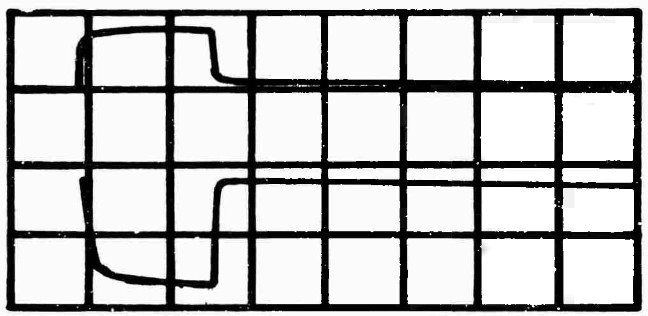
Figure 102. Three-Transistor ac-coupled Video Amplifier

well over a wide range of V_{cc} voltages from about 10 to 25 volts. Figure 103 shows static pulse tests (no radiation) for V_{cc} = 11 volts and V_{cc} = 25 volts. The output pulse was actually larger for the lower values of V_{cc}. These tests were run with the compensation junction both in and out. No difference in output was noted as long as the compensation source voltage was greater than about 10 volts. With V_x less than about 10 volts, the output pulse dropped by about a factor of 5, indicating that one of the compensation junctions was becoming forward-biased, resulting in a reduction in gain due to negative feedback.

Figure 104 shows the test results during irradiation for V_{cc} = 25 volts, at two radiation levels, and with and without compensation. V_{x1}, V_{x2}, and V_{x3} were varied simultaneously at the same value. Further reduction of the output response with compensation should be possible by individual adjustment of the V_x voltages.

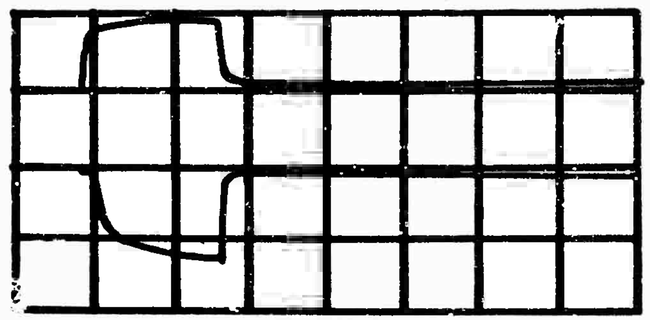
7. Three-Transistor dc-Coupled Amplifier

Figure 105 shows the circuit diagram for a three-transistor dc-coupled amplifier which was experimentally tested. This amplifier is a high-voltage amplifier shown on pages 2 to 30 of the Handbook of Selected Semiconductor Circuits of the Bureau of Ships (reference 20). The arrangements of T1, T2, and T3 permit the supply voltage of



10 µs/cm

a) V_{cc} = 11 v,
Upper: V_{in}, .05 v/cm
Lower: V_{out}, R_L = 50Ω ,
1 v/cm



10 µs/cm

b) V_{cc} = 25 v,
Upper: V_{in}, .05 v/cm
Lower: V_{out}, R_L = 50Ω,
1 v/cm

Figure 103. Static Pulse Test of Video Amplifier

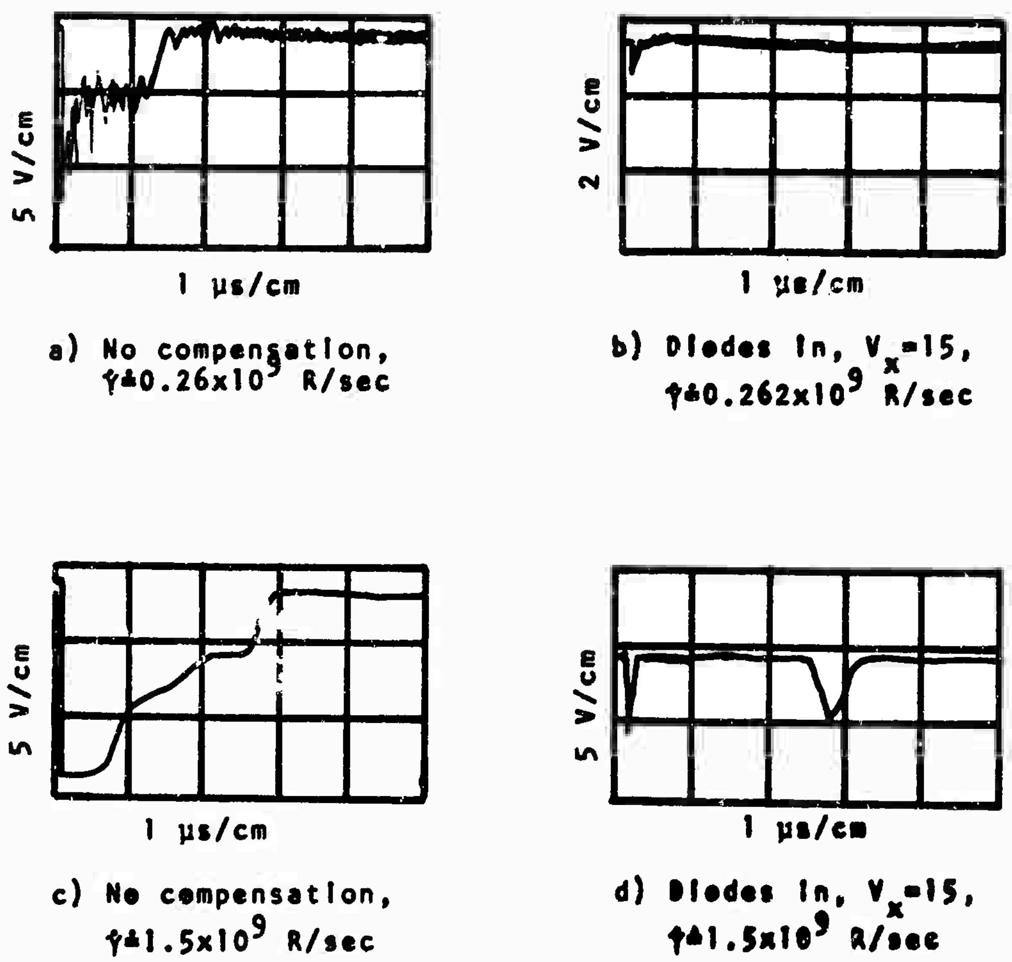


Figure 104. Test Results for Three-Transistor Video Amplifier

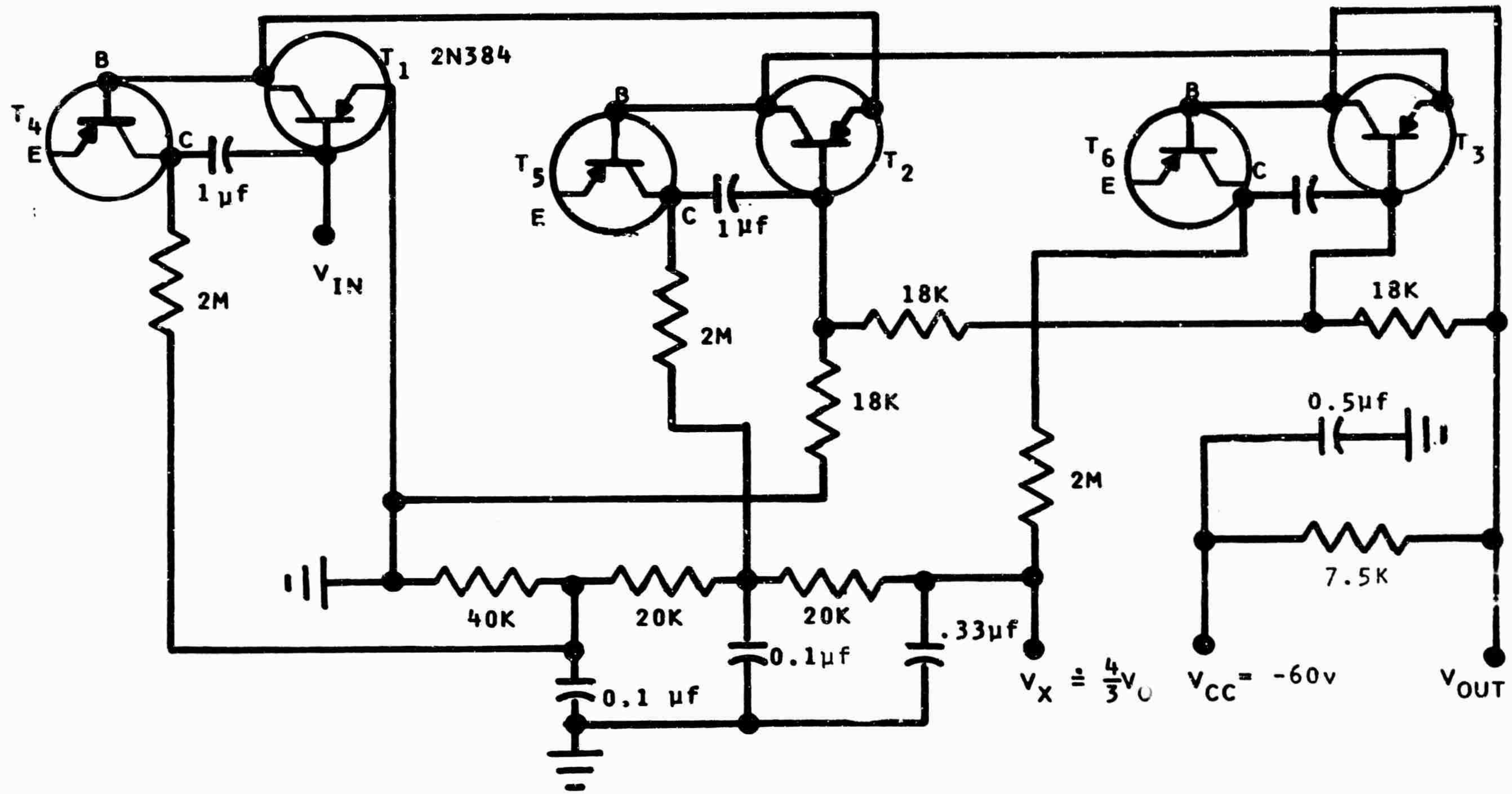


Figure 105. Three-Transistor dc-coupled Amplifier

-60 volts to be divided among the transistors so that the collector voltage of each is within the rated value of -30 volts for the 2N384.

As an example of the use of collector-to-base compensation, the required compensation junction voltages for T4, T5, and T6 are worked out in some detail as follows.

Let

V_o = quiescent output voltage for some value of V_{IN};

V_{C1} = static collector-to-ground voltage of T1;

V_{B1} = static base-to-ground voltage of T1;

V_{CB1} = static collector-to-base voltage of T1;

V_{xj4} = static compensation junction voltage of T4; etc.

Then, the following equations define the steps required to determine the compensation junction voltage, V_x, and the voltage-divider network resistances.

$$V_{C3} = V_o, \quad V_{C2} = 2/3\ V_o, \quad V_{C1} = 1/3\ V_o \tag{136}$$

$$V_{B3} = 2/3\ V_o, \quad V_{B2} = 1/3\ V_o, \quad V_{B1} = V_{IN} \doteq 0 \tag{137}$$

$$V_{CB3} = 1/3\ V_o, \quad V_{CB2} = 1/3\ V_o, \quad V_{CB1} = 1/3\ V_o - V_{IN} \doteq 1/3 V_o \tag{138}$$

$$V_{xj6} = V_{x6} - V_o, \quad V_{xj5} = V_{x5} - 2/3 V_o, \quad V_{xj4} = V_{x4} - 1/3 V_o \tag{139}$$

If the active device collector-to-base voltage is made equal to the compensation junction voltage,

$$1/3\ V_o = V_{x6} - V_o,\ 1/3\ V_o = V_{x5} - 2/3\ V_o,\ 1/3\ V_o \doteq V_{x4} - 1/3\ V_o \tag{140}$$

or make

$$V_{x6} = 4/3\ V_o,\ V_{x5} = V_o\ ,\ V_{x4} = 2/3\ V_o \tag{141}$$

As

$$V_x = V_{x6} = 4/3\ V_o \tag{142}$$

make,

$$V_{x5} = V_o = 3/4\ V_x \text{ and } V_{x4} = 2/3\ V_o = 1/2\ V_x \tag{143}$$

The voltage-divider network of 40K, 20K, and 20K across V_x will accomplish the required relationships between V_x, V_{x5}, and V_{x4} when $V_x = 4/3\ V_o$. This value for V_x would represent the minimum value to try.

In most cases V_x should be made slightly higher than $4/3\ V_o$ to make the compensation photocurrent slightly larger than the active device photocurrent.

The experimental results are shown in figures 106 and 107 at $\dot{\gamma} = 0.2 \times 10^9$ R/sec and $\dot{\gamma} = 1.7 \times 10^9$ R/sec, respectively. For $V_b = 0$, $V_o = 51$ volts; $V_b = 0.23$ volt, $V_o = 40$ volts;

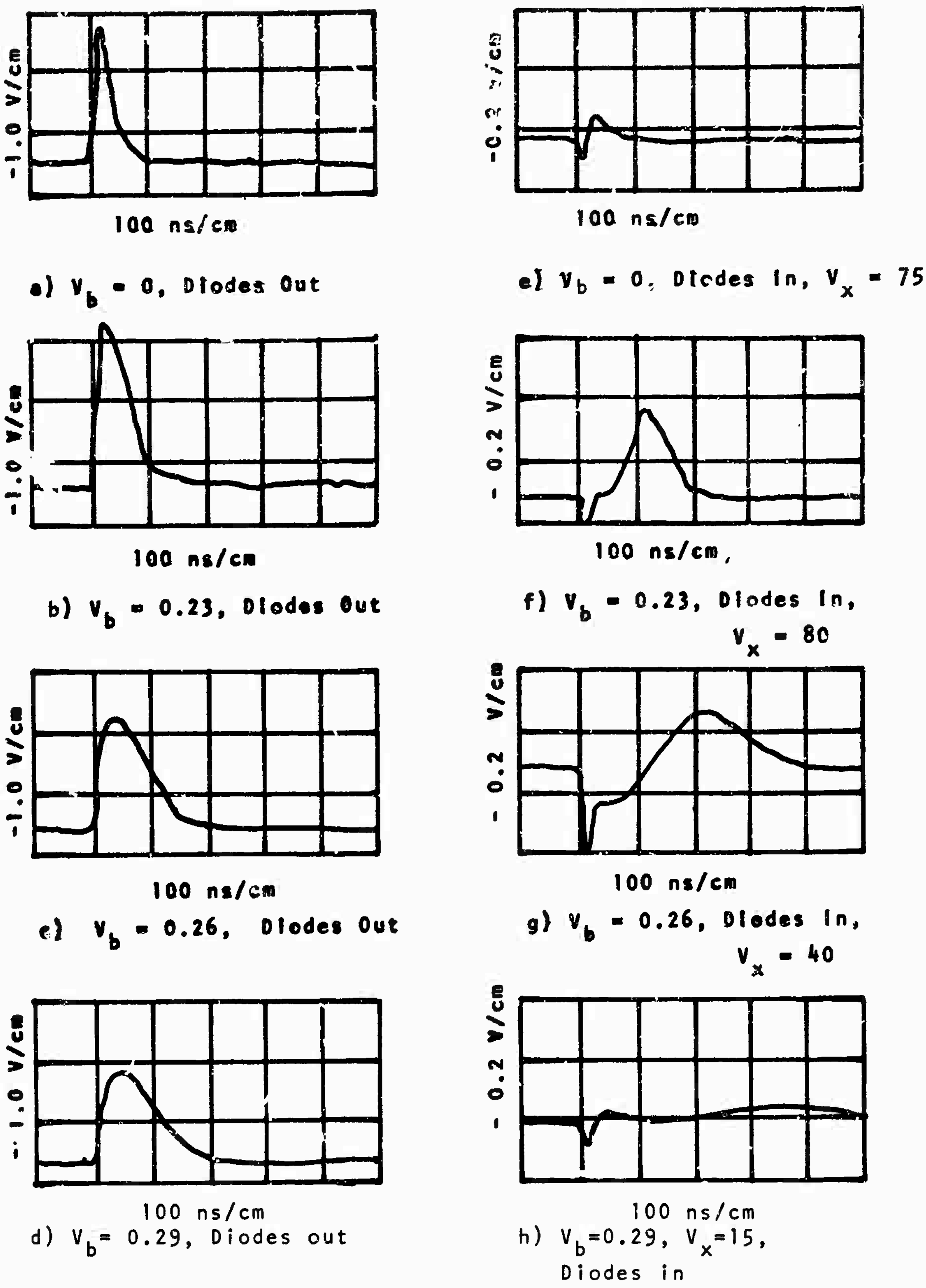


Figure 106. Three-Transistor dc-coupled Amplifier, $\dot{\gamma} \doteq 0.2 \times 10^9$ R/sec

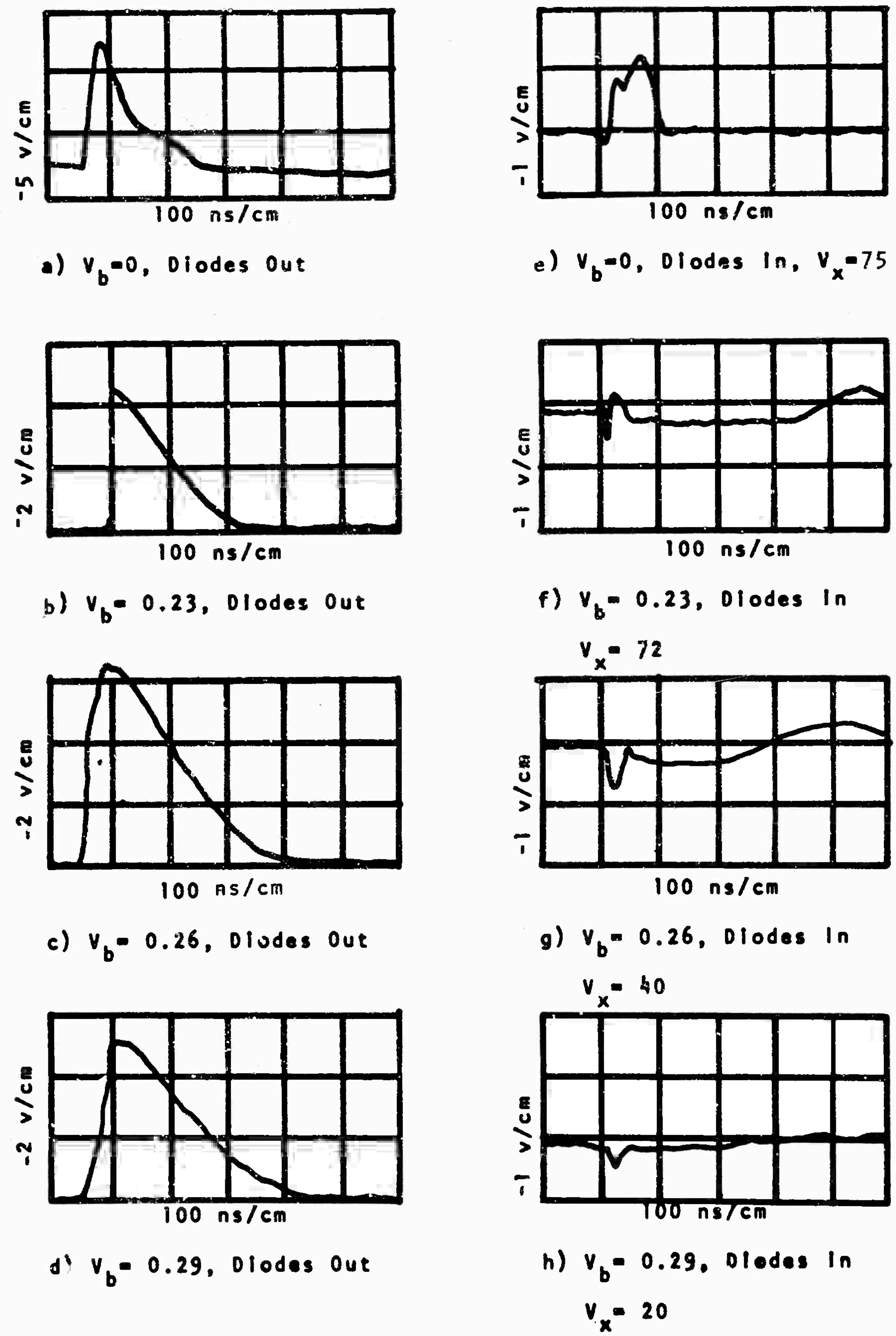


Figure 107. Three-Transistor dc-coupled Amplifier,
$\dot{\gamma} \doteq 1.7 \times 10^9$ R/sec

V_b = 0.26 volt, V_o = 20 volts; and V_b = 0.29 volt, V_o = 10 volts. From the figures it is seen that $V_x = 4/3\ V_o$ is a close first estimate, but it is low. Also, note that the pulse output drawings are inverted because of the type of plug-in unit used on the oscilloscope.

The reduction in the output pulse during irradiation was quite good. Reductions of up to about 10 to 1 were achieved.

8. <u>Monostable Flip Flop</u>

The circuit for the monostable flip flop tested is shown in figure 108. This is the same circuit presented on page 59 of reference 21, except that a compensation junction, T3, has been added from the collector to the base of T1. T1 is cut off and T2 is near saturation when no input pulse is present. The normal operation of the circuit is that an input pulse turns T1 on and results in T2 being cut off. The result is a positive output pulse as shown in the static pulse test results in figure 109a. As T2 is normally near saturation, no compensation junction was required for it.

For no compensation, the unit triggered during irradiation at $\dot{\gamma} \doteq 1.35 \times 10^9$ R/sec (figure 109b) but did not trigger at this level with collector-to-base compensation (figure 109c). In figure 109c only a small, narrow, negative output spike is present (as would be expected) from T2 in saturation. The

circuit was also tested at this level with base-to-ground compensation. The circuit triggered (as shown in figure 109d); hence, no additional testing of this mode of compensation was made.

Next, the circuit was placed as close as possible to the radiation source. The circuit did not trigger (as shown in figure 109e); only a small narrow spike was present. Without the collector-to-base compensation, at 10^{10} R/sec, the flip flop was forced into a multiple triggering mode (as shown in figure 109f) which stopped after a few hundred ms. These results imply that this monostable flip flop can be hardened up to 10^{10} R/sec, using collector-to-base compensation.

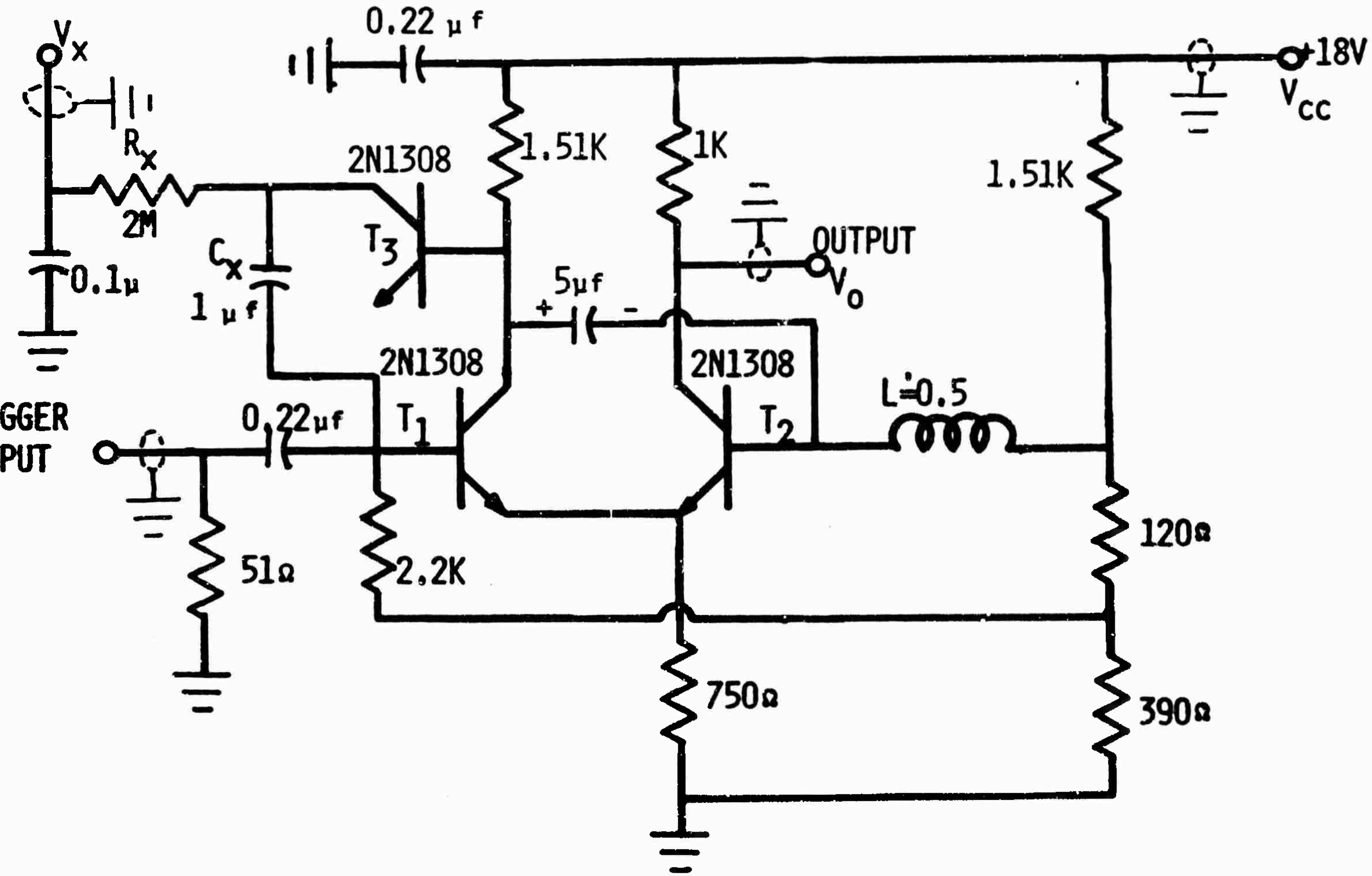
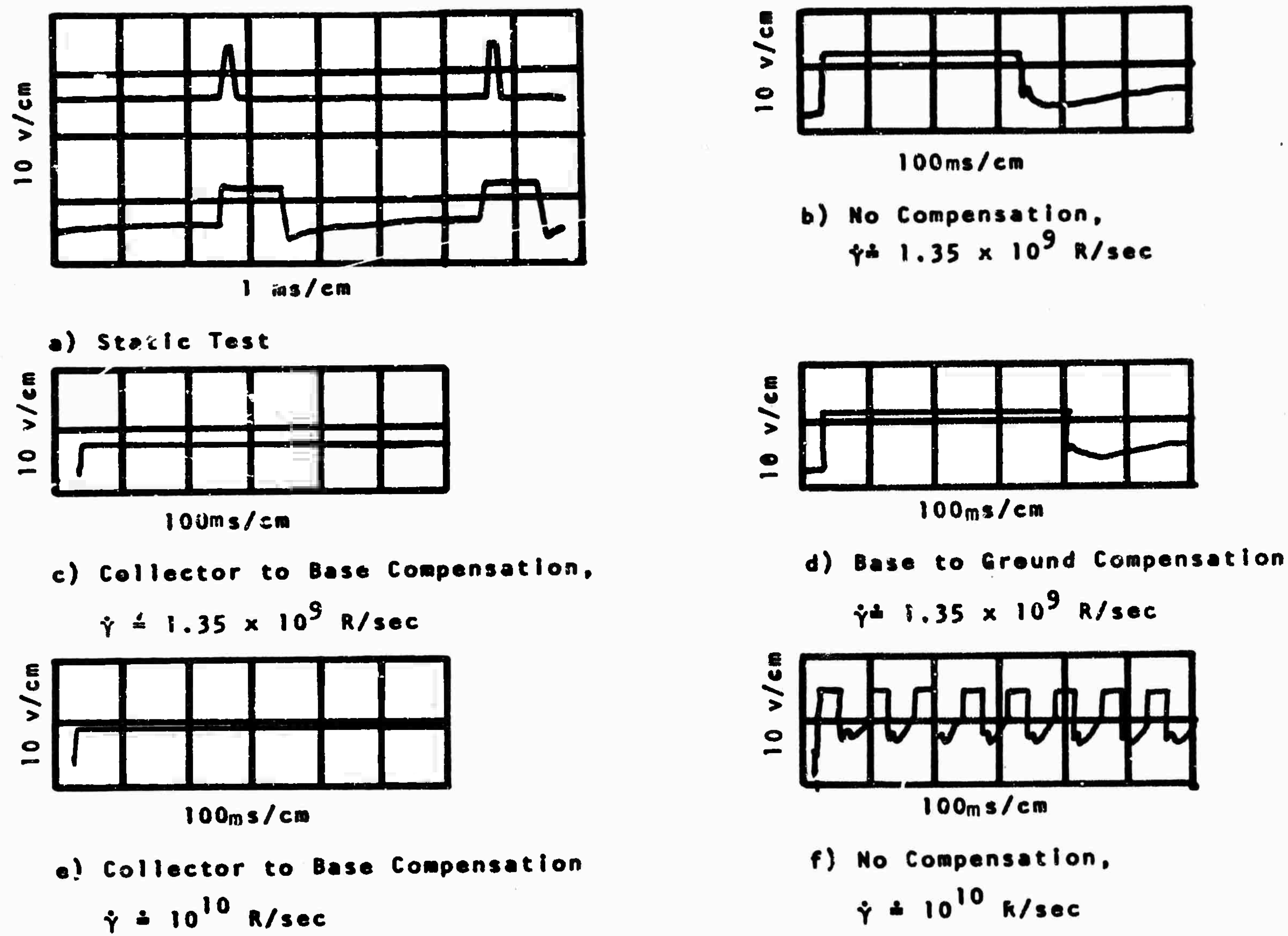


Figure 108. Monostable Flip Flop



a) Static Test

b) No Compensation, $\dot{\gamma} \doteq 1.35 \times 10^9$ R/sec

c) Collector to Base Compensation, $\dot{\gamma} \doteq 1.35 \times 10^9$ R/sec

d) Base to Ground Compensation, $\dot{\gamma} \doteq 1.35 \times 10^9$ R/sec

e) Collector to Base Compensation $\dot{\gamma} \doteq 10^{10}$ R/sec

f) No Compensation, $\dot{\gamma} \doteq 10^{10}$ R/sec

Figure 109. Test Results for Flip Flop

SECTION VI

SUMMARY AND CONCLUSIONS

Common-Emitter Amplifier. For this amplifier, reductions in the radiation response of approximately 10 to 1 were demonstrated, using collector-to-base compensation. Base-to-ac-ground compensation could also be used, but the results were not as good. For the saturation region of operation, compensation should not be used. The radiation levels considered are up to 0.5×10^{10} R/sec.

Common-Base Amplifier. This amplifier has low transient-radiation response. Collector-to-ground or output-to-ground compensation may be used for any bias region of operation; however, the reduction in transient response is modest. The reduction to expect from a well-designed stage is about 3 to 1 to 5 to 1.

Common-Collector Amplifier. Collector-to-base or base-to-ground compensation may be used for this amplifier. These techniques should yield approximately a 5-to-1 reduction in transient-radiation output response.

Common-Base to Common-Collector Amplifier. This amplifier arrangement has inherent radiation resistance. However, to achieve proper compensation, the primary photocurrent of the common-collector amplifier must be made larger than that for the common-base stage. Approximate equations showing the required relationship between two photocurrents are developed.

<u>General Comments</u>. Junction compensation may be advantageously applied to ac or dc amplifiers in cascade. The techniques also apply for pulse circuits such as flip flops or logic circuits. For pulse circuits, even higher radiation resistance than 0.5×10^{10} R/sec should be achievable by overcompensating, if pulse outputs of certain polarities are not considered a system failure.

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The reduction of the effects of transient gamma radiation on transistor circuits by using reverse-biased junctions placed at circuit points where they produce primary photocurrents that cancel out or compensate for the transient-radiation responses of the original circuit is evaluated. Approximate equivalent circuits which include junction compensation and approximate equations for engineering-design hardening criteria are developed. Selected circuits exposed to transient ionizing radiation environments, with photocurrent compensation and without photocurrent compensation, were analyzed using a CDC 6600 digital computer and the CIRCUS analysis program. These computed results were compared to the responses actually observed when the items were exposed to a radiation environment at the Air Force Weapons Laboratory's 2 Mev flash X-ray facility. With good design and for certain bias regions of operation, the peak magnitude of the transient-radiation response of an amplifier can usually be reduced by a factor of 3 to 1 to 10 to 1 for radiation levels up to approximately 0.5×10^{10} R/sec.

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